SUSTAINABLE COOLING TECHNIQUES:
THE STATE OF THE ART

by

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12th September 2008

A Dissertation submitted in part fulfilment of the

Degree of Master of Science Built Environment:

Environmental Design and Engineering

UNIVERSITY COLLEGE LONDON

THE BARTLETT SCHOOL OF GRADUATE STUDIES

Acknowledgments

This paper has benefited from the advice and expertise of my supervisor Dr. Dejan Mumovic who guided me and made the research feasible.

I would like to thank Dr. Ben Croxford, who, as a course director, provided all students with support and encouragement.

I would also like to thank Adrian Hobson and David Anderson, the Facilities Managers of the National Assembly for Wales and the School of Slavonic and East European Studies respectively, whose advice and information was important for the completion of this study.

I would also like to thank the Aristotle University of Thessaloniki, who has sponsored my studies in the UK.

Above all I would like to thank my parents for their support and love.

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Abstract

Passive design was considered significantly in architecture of early ages but after the industrial revolution it gave its place to the technologies like HVAC systems. However, in early decades with the depletion of fossil fuels, the increase of global temperatures and climate change there has been a great need of finding alternatives that are energy efficient. Sustainability is a term which is widely used nowadays, and is regarded as a state of indefiniteness, using natural sources that are never depleted.

This paper aims to define sustainability in cooling buildings. A number of previous studies on the field of low energy cooling of buildings inspired this research with the following questions: What identifies the strategies for low-energy cooling? Are current low-energy technologies, like HVAC systems, efficient enough to minimise energy consumption and CO_2 emissions? In what ways can the design of a building affect its thermal performance and how is this related to the building services? These questions are quite intriguing and can be answered by defining the sustainable cooling techniques, which are resumed in five main categories: reduction and modulation of heat gains, direct and indirect ventilative cooling, cooling energy from renewable energy sources, sustainable distribution systems and low-energy cooling technologies.

Five 'state of the art' case study buildings are enough to prove their sustainability in cooling: School of Slavonic and East European Studies building (SSEES), Swiss Re Tower, Portcullis House, National Trust Headquarters Heelis and National Assembly for Wales (NAW). Several strategies were adopted by the designers; these include ventilation, cooling and daylight. Other issues related to the cooling of buildings are facade design, energy consumption, occupant survey and thermal modelling and were also discussed. In each case study sustainable cooling techniques were sought.

Findings and results from the five buildings have shown that designers carefully considered different issues regarding sustainable cooling. The selection of sustainable cooling techniques for a building looks easy at a first sight. However, an evaluation of the actual performance of the building is quite difficult unless there is efficient information and data. Additionally, detailed analysis based on cooling loads is important in order to define the appropriate cooling techniques; this analysis is beyond the limits of this project.

1. Introduction

1.1 From passive design to today's HVAC systems

For thousands of years there were no air conditioning technologies to provide the required cooling loads to buildings. Especially in hot climates Roman, Arabic and Greek architecture were using their design as the only means of cooling the structures. The use of enough thermal mass to temper the internal conditions together with appropriate shading and urban design, the use of light coloured surfaces as well as ponds or fountains for evaporative cooling are some key design features well known from those early ages. However, after the industrial revolution and the development of technologies, passive cooling has become marginal, especially in the developed countries and has been replaced by HVAC systems (Keep Cool Project, 2005).

In the last few decades HVAC (Heating Ventilating and Air Conditioning) systems have become widespread all over the developed countries. They are widely used in non-domestic buildings in order to control their internal conditions by providing the adequate amounts of ventilation rates, heating and cooling loads within the buildings. However, they significantly contribute in greenhouse gas emissions. Besides CO_2 emissions that have a great effect on global warming, this also includes CFC's (chlorofluorocarbon 11 and 12) emissions from refrigerants which play a major role in ozone depletion. Moreover, apart from the environmental damage the energy consumption of HVAC systems is extremely high. Considering the fact that almost half -45%- of the total energy consumption in the UK originates from buildings (CIBSE Guide F, 2004) and 16% of this energy represents the energy consumed by air conditioning (Ortiz, 2006), it is obvious that air conditioning contributes dramatically to global warming and climate change.

1.2 Importance of sustainable cooling techniques

The cooling energy demand of buildings increases significantly due to the unexpected rise in global temperatures that arise from the climate change, the growing internal heat loads in buildings and the inappropriateness of the building construction. As can be seen in the Figure 1-1 cooling energy demand in Europe is continuously growing; almost a four-fold rise is predicted to occur from 1990 to 2020. It is clearly understood that the target should be to reduce the cooling energy demand in buildings. The key point in this direction is the transformation from 'cooling' to 'summer comfort', or in a word 'sustainable summer comfort' (Keep Cool Project, 2005).

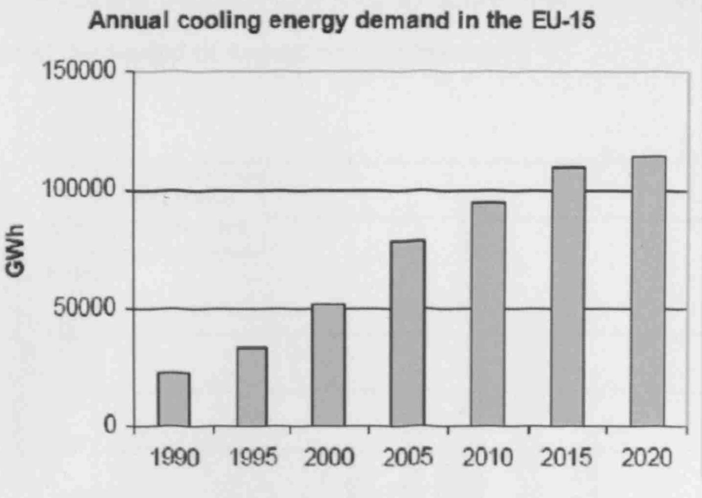


Figure1-1. Annual cooling energy demand in the European Union. (Source: Keep Cool Project 2005)

This can be done by replacing air conditioning systems with alternative means. Sustainable cooling techniques adopted in buildings have become a major challenge nowadays as they comprise energy saving, pollution free and cost efficient solutions. Under the general context of sustainability, they are yet believed to encounter the present needs without compromising the ability for future generations to meet and enjoy their needs. These techniques consist of strategies integrated into building design that minimise the use of mechanical cooling of buildings while at the same time they maximise the potential use of passive measures; that is the use of natural sources such as sun, wind or earth to cool the buildings. Thus, overheating of buildings particularly during summer period can be avoided effectively. It is imperative that during the design stage of the building the most significant steps are achieved while adopting sustainable cooling techniques

1.3 Climate Change

There is strong scientific evidence that global climate is changing (Ortiz, 2006). At the moment a significant rise in temperatures as well as a rise in the sea level, a change of precipitation and weather patterns is taking place and is about to get worse over time. The impact of this climatic change in thermal performance of buildings must be taken significantly into account when identifying cooling strategies. Summertime overheating is one of the most important issues related to the climate change and affects mainly naturally ventilated buildings (CIBSE TM 36, 2005). At the same time, it is quite interesting to have a look at the increase in the cooling degree days that is predicted to occur in UK and especially in London for the 2080s under the most likely carbon emissions scenario –medium high emissions (Appendix pp. 1). As can be seen in the following figure cooling degree days, which are an indicator of the energy used to cool a building show a rapid growth by 2080 that occurs during the whole cooling period –from May to September. However, the most significant increase takes place during the period of August and September.

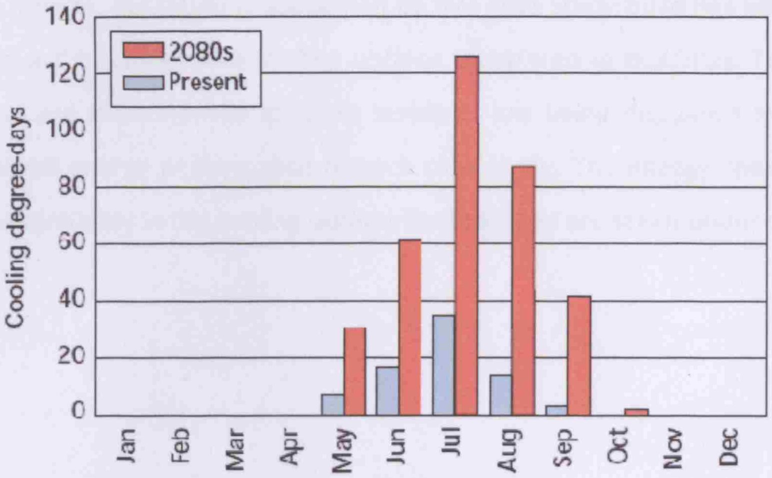


Figure 1-2. Annual distribution of cooling degree-days referred to 22oC for London, Design Summer Year 1989. (Source: CIBSE TM 36, 2005 pp 14)

Research and modelling has been made to a number of different buildings in UK by CIBSE (Chartered Institution of Building Services Engineers); for non-domestic buildings it is found that it is extremely difficult with the expected rise in outside temperatures to achieve the desired thermal comfort in indoor environment only by using passive measures, especially in big cities like London (CIBSE TM 36, 2005). The urban heat island effect of big cities should be taken strongly into consideration.

1.4 The State of the Art

In the wider context of the climate change mentioned above, this paper aims to produce a chapter entitled 'Sustainable Cooling Strategies' in the 'Handbook of Sustainable Building Design and Engineering', which consists of 28 chapters and 700pages and is going to be published by EARTHSCAN James & James on December 2008. The chapter is a report on the sustainable cooling techniques and the five case studies that are analysed in this dissertation.

This dissertation aims to support and enhance the use of the term sustainability in the cooling of buildings. It comprises a study of the low-energy cooling in buildings, where the importance of the integration of technologies and building services in the design stage of a building is highlighted. All this is presented in an innovative way through an algorithm of the sustainable techniques used to cool a building. This algorithm is a review of the current techniques adopted in order to achieve comfort cooling in buildings with the minimum required energy consumption and the minimum environmental harm is being presented.

Moreover, the paper is supported by five case study buildings which are yet believed to be 'the state the art' in sustainable cooling options integrated in buildings. The ventilation and cooling strategies that are implemented to these buildings are being discussed together with an effort to assess the overall energy performance of each case study. The energy consumption and the importance of the sustainability in the cooling options for buildings are taken under consideration where possible.

2. Suggested methodology

2.1 Brief section

This paper is based on a method already used by research groups (Wargocki 2002). Basically, this method relies in the existing scientific literature of a specific subject or several sub-subjects. A critical analysis of data is being implemented in order to distinguish what is informative and conclusive and what needs to be discarded. The results are followed by a discussion and the conclusion is presented as a consensus statement.

Based on this method, the methodology of this paper is presented further down in detail.

2.2 Literature review

The first part of the dissertation presents a literature review of the current sustainable cooling ised in buildings. Current literature was sought in order to find currently used cooling methods in the following basic key-fields:

- Passive cooling of buildings
- Low-energy cooling of buildings
- Sustainable cooling of buildings

The following databases have been systematically searched for books and papers related to the before mentioned key-fields:

- Barbour Index Online Services (technical documents from publishers including ASHRAE, BRE, BSRIA, CIBSE)
- UCL Electronic Library
- IEA Annex 28
- RIBA Electronic Library
- Conference proceedings (Indoor Air))
- Websites such as science direct and Google shcolar

The review of the cooling techniques was made in order to come up with an innovative logical path of how sustainable comfort cooling can be achieved to avoid summertime overheating; for this reason a general classification of the sustainable cooling techniques is being illustrated. In the meantime, each one of the techniques is described briefly and illustrated in most cases; fundamental mechanisms –

natural or mechanical- and issues concerning its applicability and energy use are being presented. In the end, the cooling capacities of the above mentioned techniques are being analysed and discussed together with cooling loads of buildings. Where no source is referred, these illustrations have been designed by the author.

2.3 Case studies

The second part is the most important and is dealing with the implementation of the sustainable cooling techniques in the presented case study buildings. A great amount of recently raised buildings have been sought to select the most well-known and widely published, yet believed to be the state-of-the-art in cooling options. They all comprise buildings with coherent integration of sustainable cooling techniques in their overall design. Issues related to energy performance are the most significant and were taken much into consideration when selecting the case study buildings. These buildings have either received BREEAM awards in energy consumption or they are predicted to be good practice examples according to ECON 19: energy consumption in offices (DETR, 2000). These energy issues are much related with sustainability, which is very important in addressing the selection, together with specific environmental features adopted in the case study buildings. Therefore, the selected buildings are believed to save substantial amounts of energy minimising operational costs and to provide adequate thermal indoor comfort maximising occupant's satisfaction. The selection was also addressed by the amount of information that was found.

Another factor taken into consideration for the selection of the buildings was the location. Three out of five buildings are located at the heart of the urban heat island of London. Here, the approach used in sustainable cooling is similar with the one employed in the other two buildings which are located in more rural areas: the Cardiff Bay and Swindon. A greater diversity has been avoided in order to achieve a similar 'line' of comparison when analysing the sustainable cooling techniques adopted. Non-domestic buildings have been chosen with offices use or relevant uses, such as conference or meeting rooms.

After the selection of the case study buildings a great amount of publications concerning each building have been found in two basic fields: scientific journals and also architectural and engineering journals, which are listed in the following table.

List of Scientific Journals	List of Architectural and Engineering Journals
Applied Energy	Architecture Today
Building and Environment	Brick Bulletin
Building Research and Information	Building
Building Science	Building Design
Energy and Buildings	Building Services Journal
Indoor Air	Ecotech
Indoor Built Environment	The Arup Journal
Renewable energy	Touchstone

Table 2-1. List of Scientific, Architectural and Engineering Journals, where articles were searched

The article search was basically made at the Bartlett-Environmental Studies Library. Online databases were also used and are the following:

- Barbour Index Online Services (technical documents from publishers including ASHRAE, BRE, BSRIA, CIBSE)
- UCL Electronic Library
- RIBA Electronic Library
- Building Services Journal website
- Science direct website
- Google scholar website
- Journalseek website

The designers of the buildings, both architectural companies and environmental consultant companies for the specific buildings were interviewed when gathering information regarding the sustainability in comfort cooling. A number of different environmental issues were being sought for each building and are presented further down.

- **envelope – façade – solar control**

Firstly, the key points researched were the envelope construction and the environmental performance of the building skin. These include questions regarding the existence of a climatic facade -double or triple skinned- together with comparisons of insulation values for walls and windows. Furthermore, the solar control was considered together with the use of fabric -thermal mass- in the interior of the building as the latter increases its thermal performance.

• design – ventilation strategy

Besides the construction, the design was also discussed in order to examine whether it enhanced the cooling technique adopted. In all cases, sections of the buildings have been used to illustrate the strategies implemented, especially during the cooling period. The ventilation strategy is mainly presented and discussed since it forms the fundamental cooling strategy in the UK.

• comfort objectives – design temperatures – daylight strategy

Another issue which was taken into account was the comfort objectives and the design temperatures according to the use of each building when considering its environmental –ventilation strategy. One of the most significant parameters discussed was the daylight strategy. The reason lies in the fact that artificial light plays an important role as an energy consumer and as an important internal heat source -especially in office use. Therefore, daylight strategy is much related to the cooling strategy of the building.

• low energy technologies - thermal modeling

Other issues such as low-energy technologies integrated in the design were reviewed. In one of the case studies modelling such as CFD was discussed. Thermal performance softwares were not used to assess the temperatures; the only software used was 'Weather Tool' software to plot the profile temperatures, thermal comfort and also the favourable environmental design techniques related with the cooling of the buildings.

• operational performance – post occupancy survey

The next stage was an effort of assessing the thermal performance of its case study. It was very difficult to contact the facilities department of each building and get substantial information regarding its actual performance because in most cases they do not release any data to the public. In two of the five case studies it was impossible to get access to information due to security reasons. Feedback was sought regarding data from the BMS (building management system) of each building such as figures of energy consumption and CO_2 emissions to compare with UK benchmarks. Post Occupancy surveys were also sought and where possible -already found or done- were discussed in the wider context of the actual performance of the buildings.

2.4 Discussion of analysis

Finally, a discussion of the analysis is being presented. Tables have been plotted with all the data and information from the five case study buildings and the results are being analysed to come up to general conclusions regarding the importance of sustainability in comfort cooling for buildings.

3. Review of sustainable cooling techniques

3.1 Brief section

The definition of sustainable cooling techniques was essential in order to indicate basic cooling methods and their integration in complex buildings, which is shown on the next chapter of the case studies. Moreover, this review of the techniques was made for the purposes of the chapter of the book, as mentioned previously.

As seen in the following figure building design should not be considered as a separate element for the architects. Instead, it should be considered together with the incorporation of low-energy technologies and building services by the engineers. Architects together with engineers should co-operate and apply energy efficient strategies from the early stages of the design of a building to provide the cooling, as well as the heating, loads needed in every specific building study. In this way, this approach is more sustainable than using an HVAC system from the beginning and can be achieved by applying a number of sustainable cooling techniques that can be applied to all types of buildings.

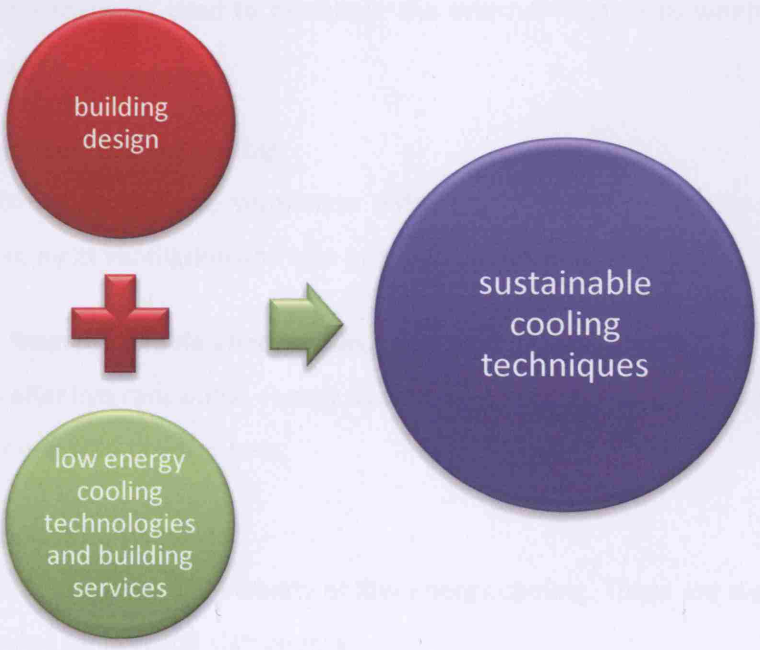


Figure 3-1. Definition of sustainable cooling technologies

After a review of the low energy cooling design, strategies and technologies, a logical path was invented and is presented in figure 3-2; five main categories of sustainable cooling techniques can be used to achieve sustainable cooling in buildings and are presented briefly further down.

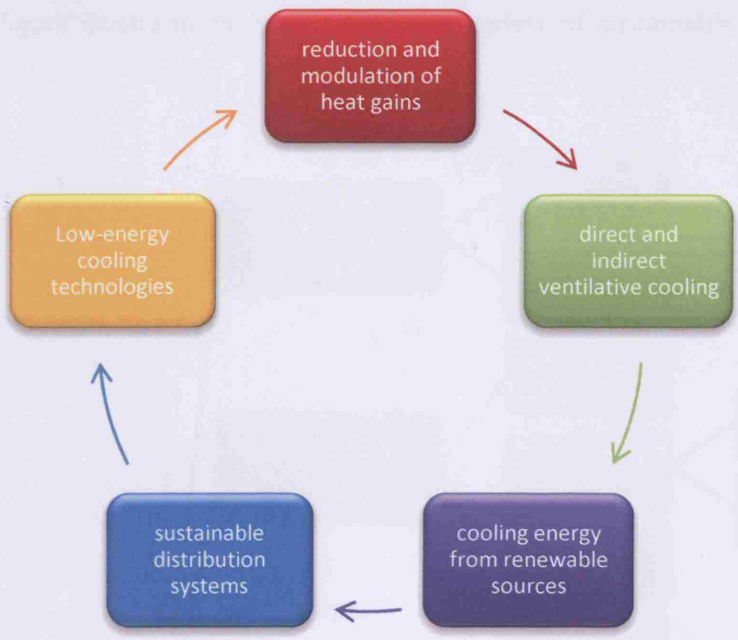


Figure3-2. A logical path of achieving comfort cooling with different sustainable cooling techniques.

• **Reduction and modulation of heat gains**:

It comprises all the methods used to modulate the internal heat gains within a building as well as reduce the solar gains.

• **Direct and indirect ventilative cooling:**

It consists of techniques that use ventilation with mostly natural means to cool buildings; that is natural ventilation, night ventilation and also mixed-mode ventilation.

• **Cooling energy from renewable energy sources:**

Ground is a very effective renewable energy source which can provide sufficient amounts of cooling, using either air or water to transfer heat.

• **Sustainable distribution systems:**

They can be used to maximise the viability of low energy cooling. These are displacement ventilation, chilled beams, chilled ceilings and slab cooling.

• **Low energy cooling technologies:**

Comprise evaporative cooling, a major technique, known from early ages. In addition here we find technologies used in air-conditioning systems to maximise the energy saving by re-using the conditioned air or the waste heat.

The following figure illustrates in more detail, the variety of sustainable cooling techniques in an algorithm.

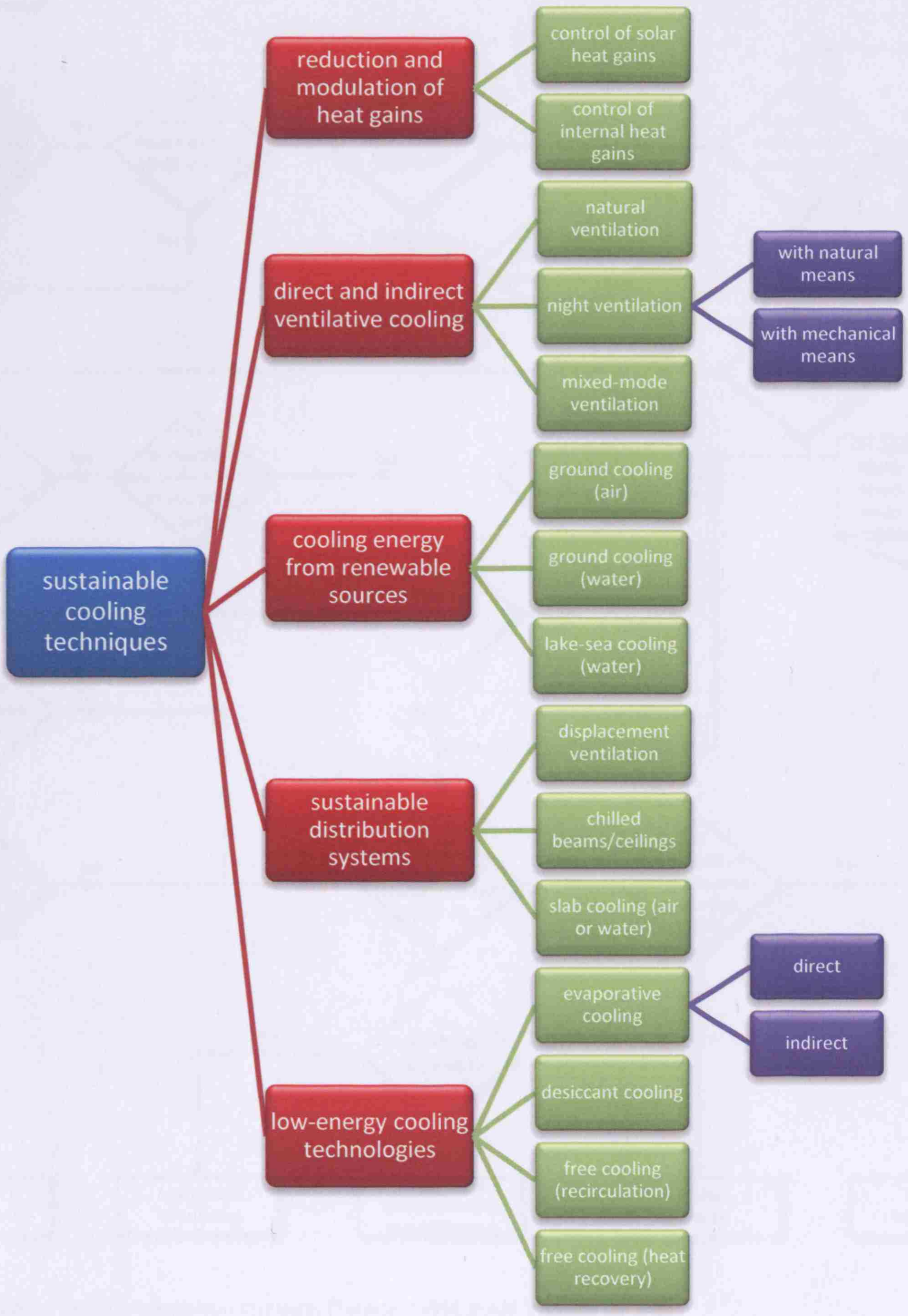


Figure3-3. Diversity of sustainable cooling techniques

As mentioned before, this algorithm is of great importance. This summary of the techniques can help to define the appropriate strategies that have to be adopted in various types of buildings to provide sustainable cooling.

3.2 Selection of a Ventilation Strategy.

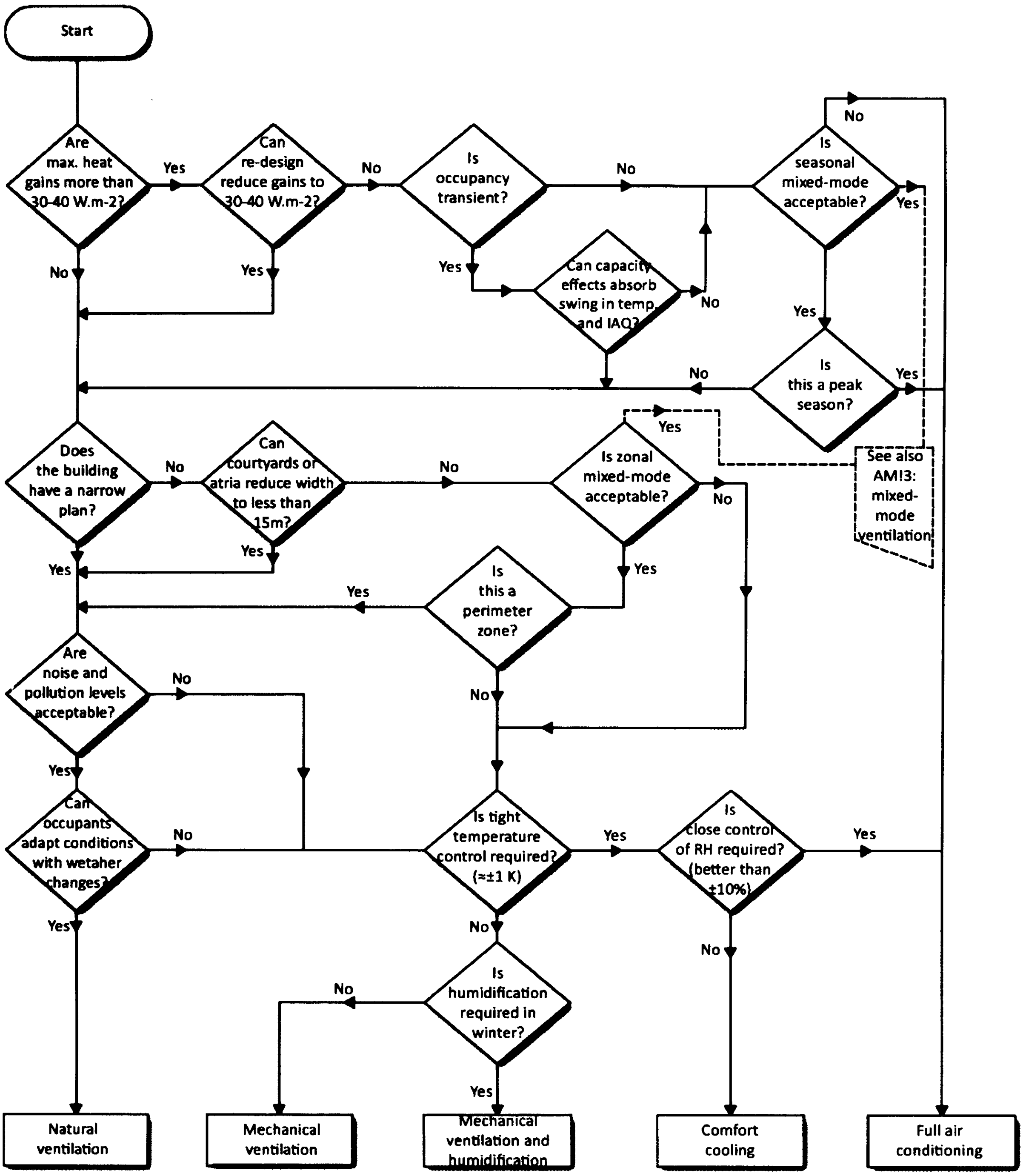


Figure 3-4. Path to select a ventilation strategy. (Source: CIBSE guide B, 2005, pp 2-8)

Ventilation strategy plays a major role for the cooling of a building especially in the UK. Due to the climate profile, the outside air temperatures are usually below comfort zone even in summer. Thus, the ventilation strategy can address the cooling of the building (CIBSE guide B, 2005). Figure 3-4 shows the path of selecting the ventilation strategy. As can be seen it is affected by a number of parameters including site analysis, internal heat gains, plan layout, temperature and relative humidity control. The most important thing that should be taken into consideration is the use of the building and the occupancy patterns. Air infiltration is addtionally a major factor; high infiltration rates can obliterate a ventilation strategy. As can be seen in Figure 3-4 there is a great diversity of ventilation strategies including natural ventilation, mechanical ventilation, mechanical ventilation and humidification, comfort cooling and full air conditioning.

3.3 Reduction and modulation of heat gains

3.3.1 External heat gains

The first step to address sustainable cooling is by reducing and modulating the heat gains. There is a number of ways which can reduce significantly the heat entering a building. This heat stems from solar radiation and also from temperature difference between the outdoor and indoor environment. Building envelope should be designed in such a way to minimise these heat gains during summer period; this can be achieved with high performance building envelopes (CIBSE TM29, 2005). The parameters that should be taken into consideration concern the envelope's insulation, the facade's solar shading and the air infiltration. The following figure represents the recommended U-values for walls and windows and also the recommended solar shading coefficient for high performance building envelopes. Climate or active facades must be also mentioned; they comprise advanced facades with ventilative cavities which allow air to pass through them. Therefore, they enhance the thermal performance of the building envelope either by reducing further the U-value of the facade or by reducing significantly solar heat gains.

Insulation of high performance building envelopes	
walls	up to 0.3W/m^{2}K
windows	1.0 - 2.0W/m^{2}K
solar shading coefficient	0.2 - 0.3

Table 3-1. Recommended values for high performance building envelopes.

3.3.2 Internal heat gains

Besides the heat which enters a building from the outside to the inside, there is also heat which is emitted in the interior of a building; that is internal heat gains which include heat emitted by people occupying a space, lighting fittings and also electric devices. There are many ways of modulating this heat. Firstly, energy efficient equipment and lighting can reduce significantly internal heat gains. However, heat gains from people are difficult to cope with, especially in spaces with high occupancy patterns. A good way of modulating heat emitted by occupants is to spread the heat gains within the internal spaces in order to avoid peaks. This can be achieved at the design stage, at the same time when designing the spaces and deciding the occupancy patterns together with the target temperatures for the different uses of the internal spaces (CIBSE Guide A, 2006).

3.4 Direct and indirect ventilative cooling

Direct and indirect ventilative cooling comprises the most energy efficient method of cooling the building due to the minimum amounts of energy consumed. These methods are presented further down.

3.4.1 Natural Ventilation

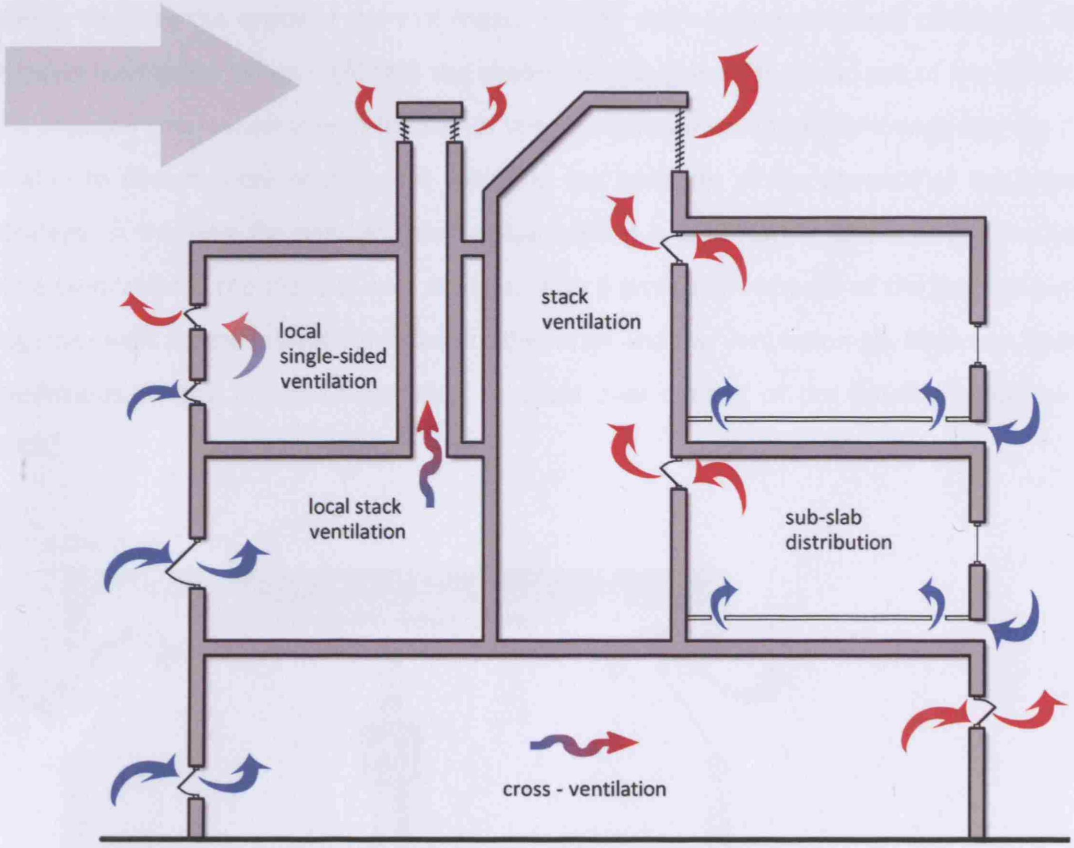


Figure 3-5. Cooling a structure by different types of natural ventilation

Natural ventilation uses fresh cool air from outdoors to cool the building. The introduced air that replaces the contaminated indoor air, is heated and then exhausted throughout building openings. The air flow path defines the different ventilation modes, as illustrated in figure 3-5; single sided-ventilation, cross ventilation, stack ventilation and sub-slab distribution. The cooling capacity of natural ventilation is not very high and depends mainly on the temperature of the outside air. Therefore, in most cases and especially in non-domestic buildings situated in the urban heat island, where outside temperatures are higher than in the rural areas, natural ventilation cannot cope with the internal heat gains. The key aspect in natural ventilation is the building layout which can enhance the air flow (CIBSE Guide A, 2006).

3.4.2 Night Ventilation (natural or mechanical)

Cooling can be achieved indirectly using the night ventilation strategy. This strategy takes advantage of night temperatures, which are lower than daytime ones and usually below thermal comfort in cool climates. The concept of this strategy is based on cooling the structure of the building with the use of either natural or mechanical ventilation during the night. Figure 3-6 depicts how this strategy works; during daytime the exposed thermal mass –usually slab- provides radiant cooling by absorbing the internal heat gains. When night falls the absorbed heat gains are spread out of the building by cooling the exposed thermal mass with the use of ventilation. As a result, the following day the thermal mass is able to absorb more heat than it would in the occasion of the absence of the night ventilation strategy; in this way the need for mechanical cooling is significantly reduced. The key factor in night time ventilation is the thermal heat storage; thus, a good performance of the thermal mass is needed together with a good interaction between the latter and the ventilation air. However, there must be a meticulous control of night ventilation to avoid over cooling of the building structure (CIBSE KS3, 2005).

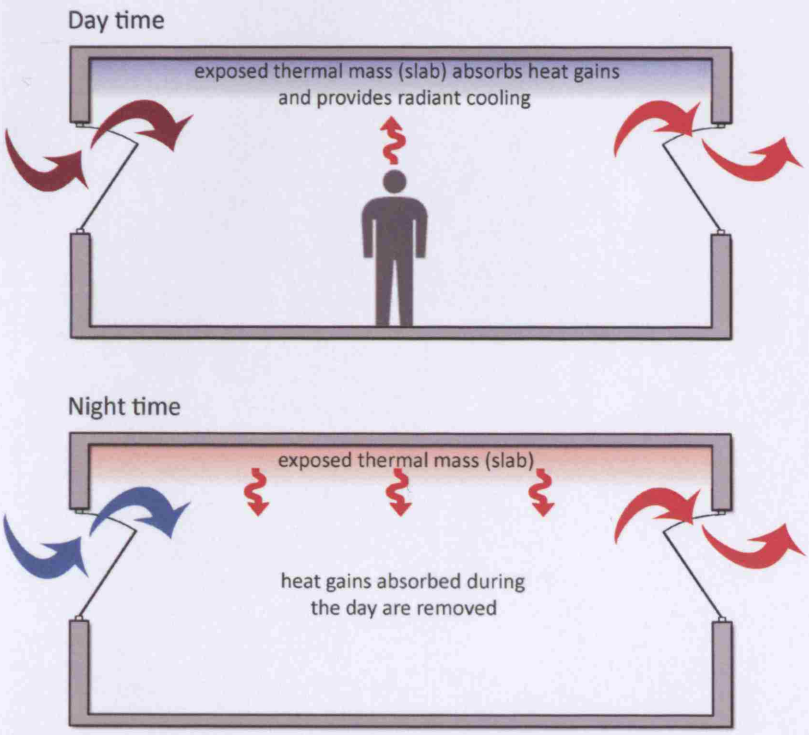


Figure3-6. Night ventilation strategy.

3.4.3 Mixed-mode ventilation

Mixed mode ventilation comprises a system which combines natural and mechanical ventilation. It is usually used in non-domestic buildings and especially in London, where as mentioned before natural ventilation is not sufficient enough for cooling due to the urban heat island. There are three main types of mixed-mode ventilation:

• Contingency mixed-mode, where each system –natural and mechanical- is used to back up one another
• Complementary mixed-mode, where both systems operate together in concurrent or changeover mode
• Zoned mixed-mode, where the building is separated in different zones according to different internal condition requirements.

Generally, mixed-mode systems provide effective control of the internal conditions, without compromising in the design and layout of the building. However, the energy consumption of the mechanical system must be taken into consideration in each case separately (CIBSE AM13, 2000).

3.5 Cooling energy from renewable energy sources

The use of renewable energy sources is another way of cooling buildings. Ground, lake, sea and river constitute sources that keep their ambient temperatures stable during the year and in this way can be used as a cooling or heating source (CIBSE Knowledge Series KS3, 2005).

3.5.1 Ground cooling (air)

This system uses a network of underground ducts, buried approximately at 2-4m depth. The temperature of the ground at this depth is stable at around 10-14oC in the UK. As illustrated at figure 3-7 air is supplied and being cooled through thermal exchange with the ground. The cool air is then introduced to the building or used as pre-cooled air for the ventilation plant (Smith, 2001).

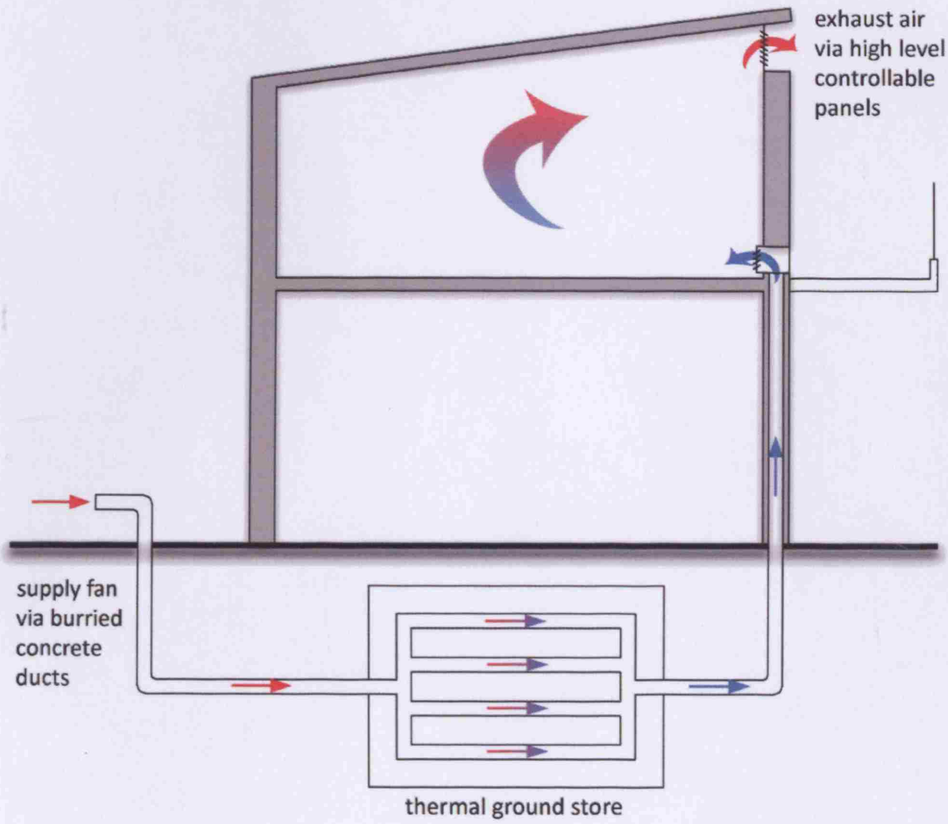


Figure3-7. Ground cooling (air) system.

3.5.2 Ground cooling (water)

This system usually uses boreholes which are buried up to 150m deep into the ground. Heat transfer takes place either from the ground or from the aquifer; in this way, water is cooled in the cold borehole and is used for cooling via a heat exchanger, which is usually a ground source heat pump.

After this process the warm water is re-injected back to the warm borehole and the procedure is repeated.

3.5.3 Lake/sea cooling (water)

This system comprises an alternative of a borehole system described in the previous sub-chapter. The cold water of a lake or a sea is extracted and passed through the heat exchanger. In this system what the depth from which water is extracted is important; the deeper the water is extracted from the colder it is and the more appropriate cooling it provides.

3.6 Sustainable distribution systems

The distribution systems that take advantage of the high water temperatures (usually 14-18oC chilled water T) to provide the adequate cooling loads provide a more viable solution for the low-energy cooling of buildings. These are three main systems: displacement ventilation, chilled beams and ceilings and slab cooling with air and water.

3.6.1 Displacement ventilation

Displacement ventilation is one of the most recent methods used especially in office buildings. The basic principle of this technique is illustrated at figure 3-8. The air is supplied at low velocities and at a lower level, usually through raised floor and creates a reservoir of cold air. This cold air is heated only when it gets into contact with an internal heat source. In this occasion it rises up and is extracted through upper level outlets, usually mounted at the ceiling. The movement of the air is enhanced from the heat emitted by the lighting fittings on the ceiling. The great advantage of displacement ventilation is that it works only where needed, that is when there is internal heat gain, and therefore is energy efficient. Another advantage is that the temperature of the air used to condition the occupied space is higher than that of the conventional HVAC systems; it ranges between 15oC and 20oC (BSRIA, 1999).

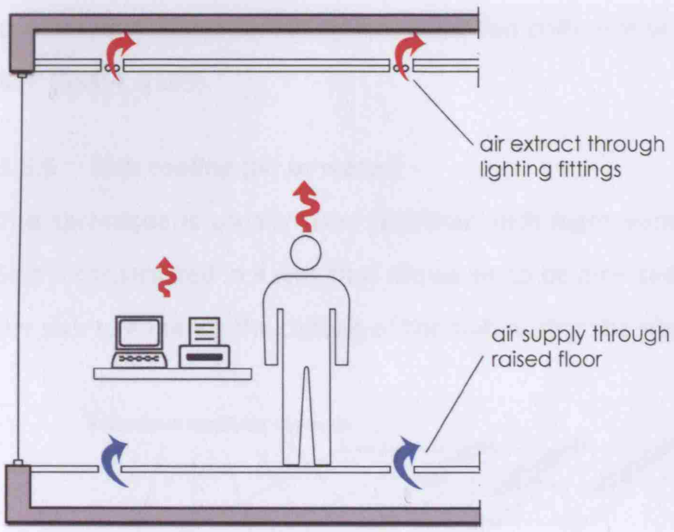


Figure3-8. Displacement ventilation system.

3.6.2 Chilled beams and chilled ceilings

Static cooling devices such as long rectangular beams, called chilled beams, or such as rectangular panels, named chilled ceilings are used to provide cooling loads within occupied spaces; chilled water is passed through these devices. They both commonly supplement other systems, like displacement ventilation. Figure 3-9 illustrates the combination of the three different systems.

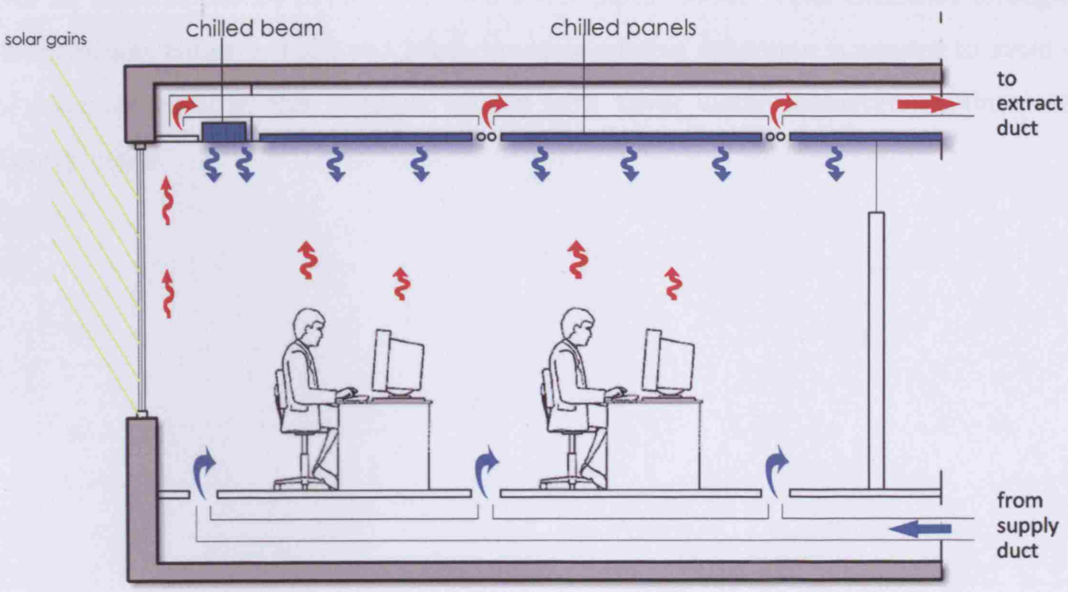


Figure3-9. Chilled beam and chilled ceiling with displacement ventilation.

Chilled ceiling provides radiant cooling, while chilled beam provides mainly convective cooling. One major advantage is that the temperature of the used chilled water is higher –between 15oC and 16oC- compared to conventional systems, like fan coils; the latter use water temperature in the range of 6-8oC (BSRIA, 1999).

3.6.3 Slab cooling (air or water)

This technique is usually used together with night ventilation to maximise the potential of cooling. Slab is constructed in a way that allows air to be directed in embedded channels. Air is passed through the slab to enhance the cooling of the slab during the night (figure 3-10).

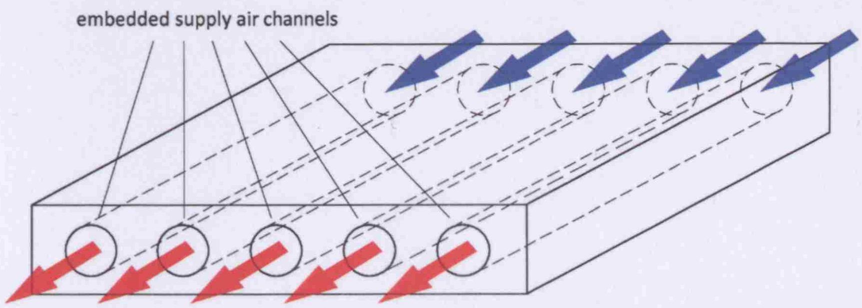


Figure3-10. Slab cooling with the use of air.

Inversely, the daytime warm air is injected through the cool slab in order to be pre-cooled before being used to either condition a space or be sent to the ventilation plant. Slab cooling technique can also be implemented by using embedded water pipes. Chilled water circulates through the pipes at temperatures between 14oC and 20oC providing cooling. Attention is needed to avoid condensation of concrete surfaces; this happens usually with lower water temperatures (International Energy Agency, 2000).

3.7 Low-energy cooling technologies

Low-energy cooling techniques include the incorporation of free cooling to an air-conditioning system which can take advantage of the weather conditions to reduce the energy consumption by shutting down the cooling plant. (CIBSE Knowledge Series KS3, 2005). They are presented further down.

3.7.1 Evaporative cooling (direct and indirect)

Evaporative cooling is a technique which had been used for thousands of years; it originates from Egypt. The principle of evaporative cooling relies on the physical process of changing water from liquid to vapour; the heat needed for the process to occur is extracted from the air. In this way, a cooling effect of the air takes place. According to Figure 3-11 the evaporative cooling can be either direct, where the incoming air is blown along a spray of cold water which cools the air before it is being used to condition a space. However, the water content of the cooled air increases. To avoid this increase in moisture indirect evaporative cooling can be utilised, where the cool air produced by the direct evaporative cooling process is passed through a heat exchanger, which cools the air supply.

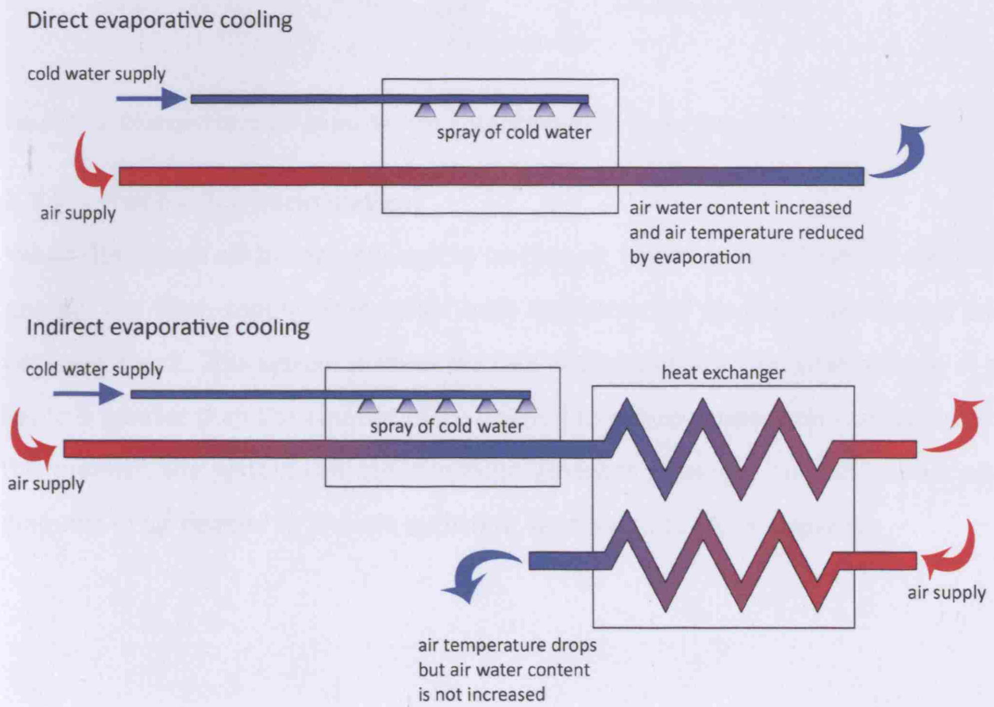


Figure3-11. Direct and indirect evaporative cooling (Source: International Energy Agency 2000)

3.7.2 Desiccant cooling

In the desiccant cooling system (figure 3-12) the extract air is used to cool the fresh incoming air. The introduced air passes through a desiccant wheel, which uses a material to achieve dehumidification;

this moisture is removed by the heated extract air. After the desiccant wheel the income air is cooled by a heat recovery device (thermal wheel); this cooling load stems from the extract air. The cooled supply air can be cooled again by passing through an evaporative humidifier. The degree of cooling can reach 8-9°C. This system works well in humid climates but not so efficiently in dry ones. Additionally, the desiccant material requires heat to dehumidify the air which can be waste heat from another system or solar energy.

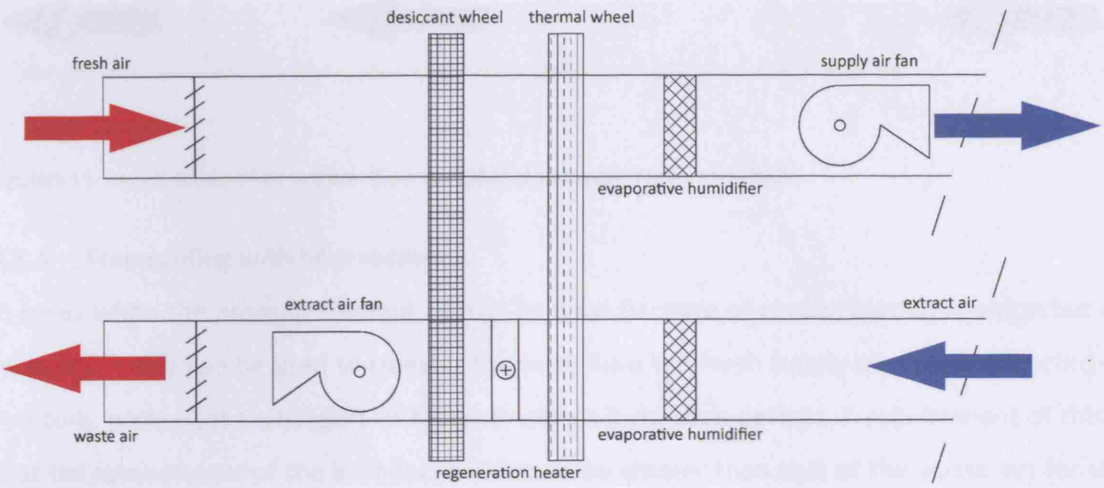


Figure3-12. Desiccant cooling system (Source: CIBSE Knowledge Series KS3, 2005)

3.7.3 Free cooling (recirculation)

When the extract air is clean enough to be reused, recirculation of extract air can take place and save energy. The fresh supply air is mixed with the extracted air then conditioned and introduced in the occupied space. This system is implemented in cases where the total volume of air needed to cool a space is greater than the amount of air needed to provide indoor air quality (minimum ventilation). In this manner, the system can use minimum amounts of supply air and extract waste air equal to the amounts of air needed to provide sufficient ventilation to the occupants.

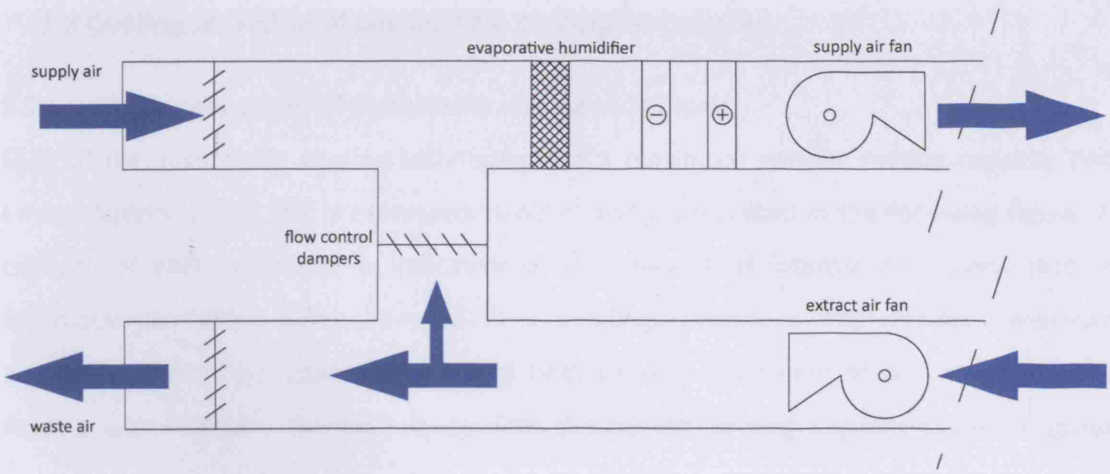


Figure3-13. Recirculation of air system. (Source: CIBSE Knowledge Series KS3, 2005)

3.7.4 Free cooling with heat recovery.

In cases when the previous method cannot be used because of contamination in extracted air, a heat recovery device can be used to transfer the heat from the fresh supply air to the extracted-waste air. Fan coils, plate heat exchangers or thermal wheels form such devices. A requirement of this system is that the temperature of the introduced air must be greater than that of the waste air; for this reason the extract air is usually cooled by an evaporative humidifier.

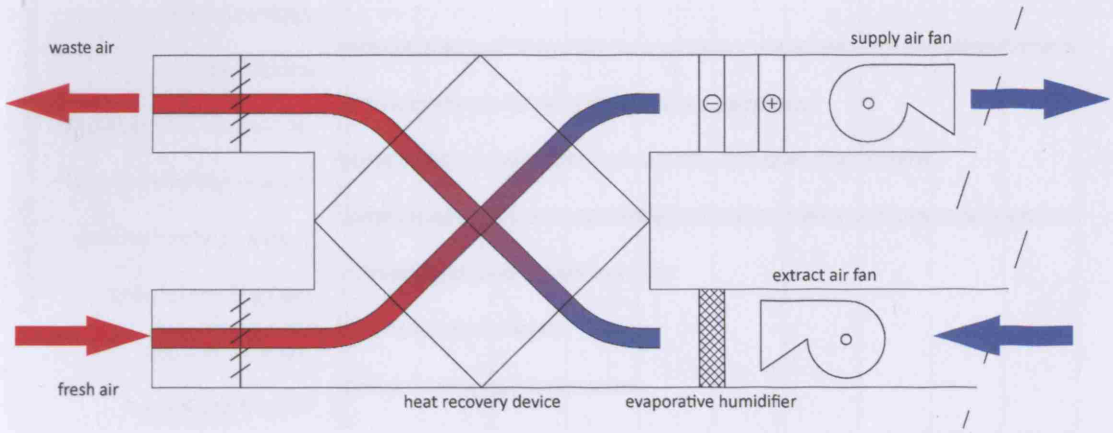


Figure3-14. Heat recovery system. (Source: CIBSE Knowledge Series KS3, 2005)

3.8 Cooling potential of sustainable cooling techniques

3.8.1 Cooling capacities of sustainable cooling techniques

Each of the sustainable cooling techniques has a maximum specific cooling capacity (International Energy Agency 2000); this is expressed in W/m^2 and is presented in the following figure. The cooling capacity of each technique is indicative of the amount of internal heat gains that the specific technique can offset when adopted in a building. Therefore, the weakest technique is night ventilation, which can cope with internal heat gains in the range of 30W/m^2. Natural ventilation follows with 40W/m^2. The techniques with the highest cooling capacity comprise ground cooling (water) and chilled beams accounting for up to 100W/m^2. However, in some cases a combination of two or three cooling techniques is being implemented especially when the building consists of occupied spaces with very high internal heat gains. This combination is usually displacement ventilation with chilled beams and/or chilled ceilings, night ventilation with slab cooling and also ground cooling with displacement ventilation.

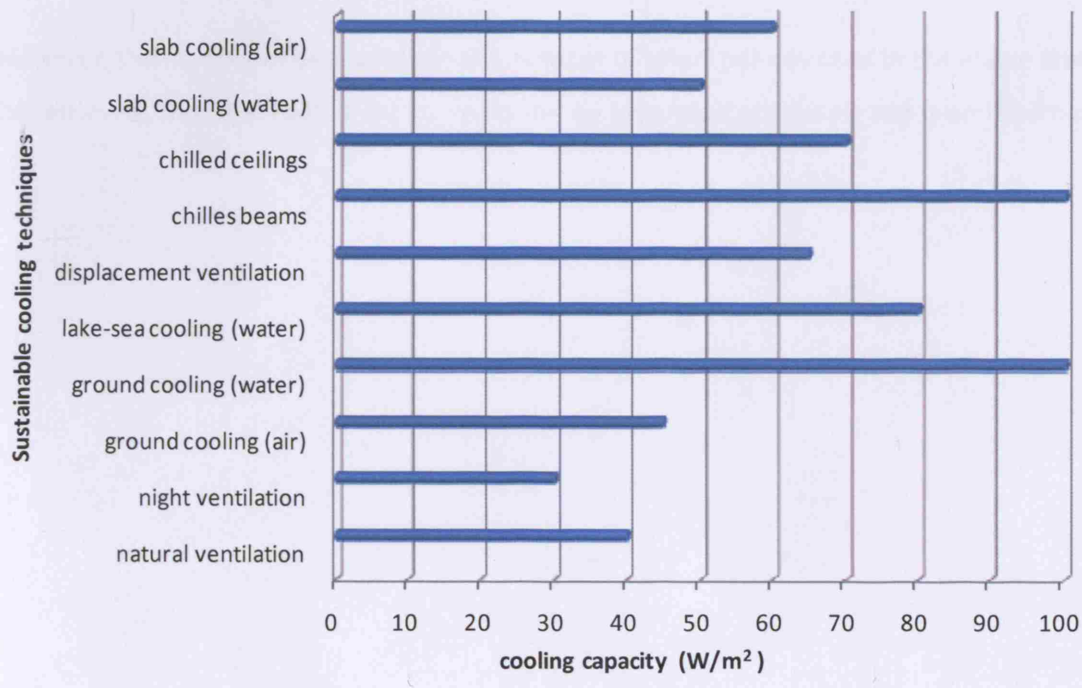


Figure3-15. Cooling potential of sustainable cooling techniques.

3.8.2 Calculation of building cooling loads

It is interesting to investigate the cooling loads of buildings to compare them with the cooling capacities of the sustainable cooling techniques. In this way assess the applicability of the techniques can be assessed.

There are three different methods of calculating the building cooling load (Ansari et al., 2005). The first one takes into account different parameters such as internal heat gain loads, direct solar radiation loads, transmission loads and ventilation/infiltration loads. These parameters encompass the sensible cooling load. However, a percentage of it must be added to give the latent cooling load. A table in Appendix pp. 1 presents an estimation of all the cooling load parameters. Other ways of calculating the cooling loads are the use of load estimation forms produced by designers/companies and also the application of computer thermal software.

An effort of estimating cooling loads for office buildings was made based on ECON 19 study (DETR, 1999). The required cooling energy given for the 4 different types of offices (see Appendix pp. 2 figure 4) is summarised in the following table.

	1. NV cellular		2. NV open-plan		3. AC standard		4. AC prestige	
	good practice	typical	good practice	typical	good practice	typical	good practice	typical
cooling (KW/m2)	0	0	1	2	14	31	21	41

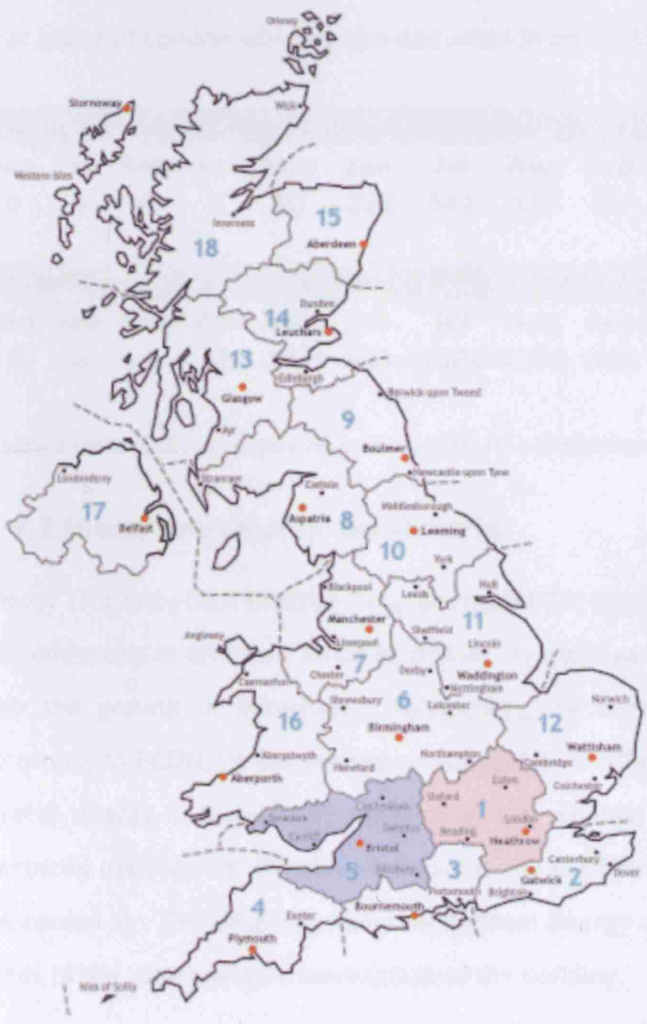
Figure 3-16. Energy consumption benchmarks for cooling

However, the number of days per year and number of hours per day used in the above study could not be retrieved. Thus, the cooling energy could not be calculated accurately and is omitted here.

4. Case study buildings

4.1 Brief section – Cooling degree hours.

The five case studies examined represent buildings with sustainable cooling techniques integrated in their design. The most important elements that contribute in keeping them cool, avoiding overheating during summer period are being discussed. Three of the buildings are located within the urban heat island of London and comprise the School of Slavonic and East European Studies (SSEES), the Swiss Re Tower and Portcullis House; the last two are situated in more rural areas, Cardiff bay and Swindon and are The National Assembly for Wales and Heelis Building respectively.



Regions

1	Thames valley
2	South East
3	South
4	South West
5	Severn Valley
6	Midland
7	West Pennines
8	North West
9	Borders
10	North East
11	East Pennines
12	East Anglia
13	Wales
14	W Scotland
15	E Scotland
16	NE Scotland
17	Northern Ireland
18	NW Scotland

Figure 4-1. Cooling degree regions for UK (Source: CIBSE TM 41 2006)

It is interesting to look at the cooling degree hours for the areas where the above mentioned buildings are located. Cooling degree hours are indicative of the cooling load needed for a building in a specific area and are mostly used to predict the annual cooling energy needed (CIBSE TM 41, 2006).

As can be seen in figure 4-1 UK is divided in a large number of areas that have very similar weather profiles and therefore are assumed to have the same degree hours. The highlighted areas are: London (1 – Thames Valley) and Cardiff-Swindon (5 – Severn Valley).

The following table presents the cooling degree hours for these two areas with a base T of 18oC (Appendix pp. 2 for further information). As can be seen the annual cooling degree hours for Cardiff is almost one third of the one for London (Heathrow). One should also consider the effect of the urban heat island of London which is also discussed in one of the following chapters.

monthly cooling degree hours (/K*h) for base T of 18oC for CARDIFF												
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
0	0	0	5	90	222	541	410	81	3	0	0	**1352**

monthly cooling degree hours (/K*h) for base T of 18oC HEATHROW												
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
0	0	2	32	274	635	1388	1158	308	33	0	0	**3830**

Table 4-1 Monthly cooling degree hours for Cardiff and London (Heathrow)

4.2 Energy consumption benchmarks

Energy Efficiency Best Practice Programme (ECON 19) gives benchmarks for energy consumption and CO_2 emissions in different kinds of offices. Energy use in offices has dramatically risen last decades with the growth in information technology, air conditioning and intensity of use (DETR 2000). According to ECON 19 low energy consumption in offices relies mainly in good design together with careful energy management. Regarding the energy consumption for cooling, it comprises the electricity used to cool the air and also the one used to run the fans, pumps and controls to distribute the cooled air. The latter is usually the highest energy category and in several cases accounts for two thirds of the total energy consumption of the building.

The following figure illustrates the energy consumption benchmarks for four different types of offices (see Appendix pp 3) for typical examples and also for good practice examples which use energy efficient measures and thus achieve significant lower consumption.

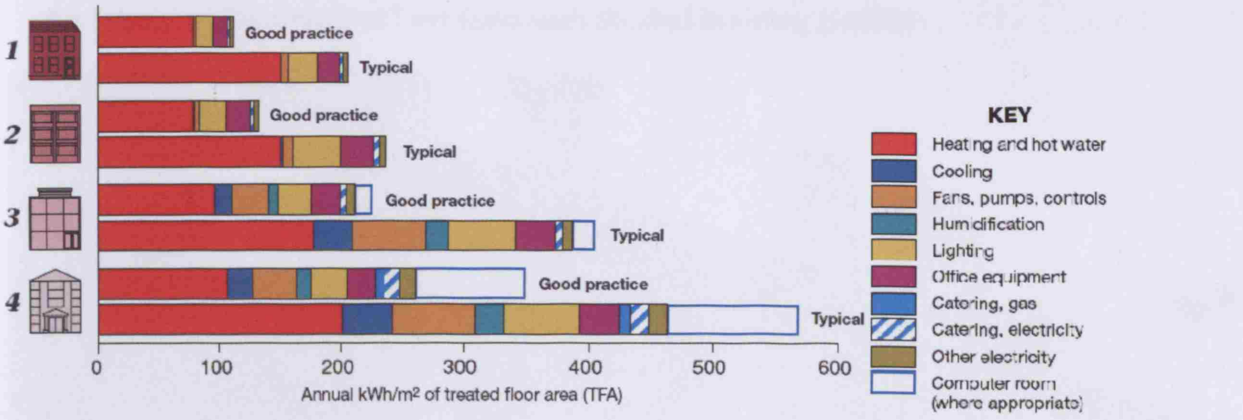


Figure 4-2. Energy use for good practice and typical examples of four types of offices (Source: DETR 2000 pp. 10)

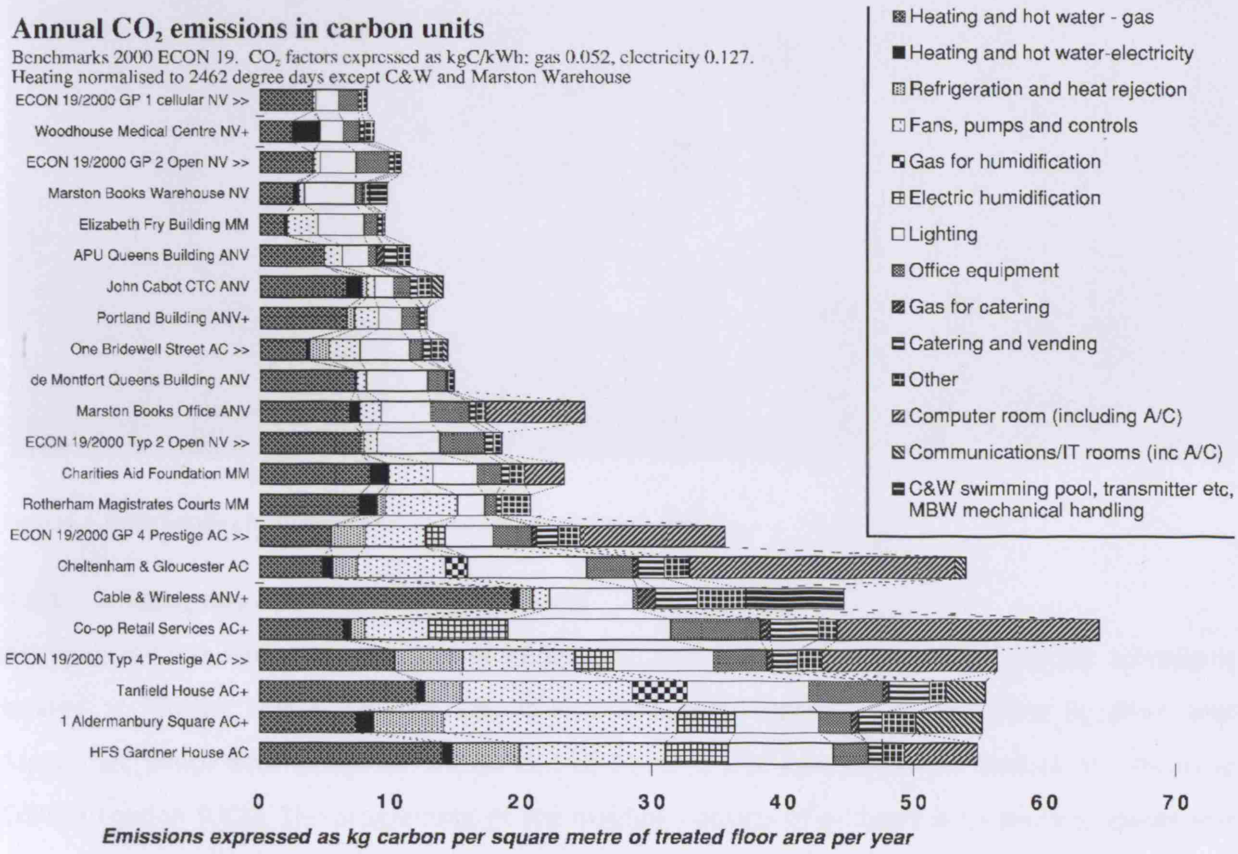


Figure 4-3. Annual carbon dioxide emissions from gas and electricity consumption. (Source: Bordass, 2001, pp. 121)

Another study has been made in 1999, called the Probe series of post-occupancy studies, and referred to 16 different types of buildings. Annual carbon dioxide emissions are presented in figure 4-3 in kgs per m^2.

4.3 School of Slavonic and East European Studies Building (SSEES)

Figure4-4. Front facade of School of Slavonic and East European Studies

4.3.1 Building description and main attributes

As highlighted at figure 4-4 the School of Slavonic and East European Studies (SSEES) building is located at Taviton Street, London, UK. It is a five-storey construction, designed by Short and Associates, which accommodates the School of Slavonic and East European Studies at University College London (UCL). The programme of the building consists of a library with reading spaces and several offices. The general concept was to build a large naturally ventilated building, which is yet the first one within the urban heat island of London which uses passive downdraught evaporative cooling. The key issue in the environmental strategy is the seasonal operation mode, which gives the opportunity to the building to acquire different ventilation modes dependent on the external weather profiles (Lomas, 2004).

The following sub-chapters refer to attributes of the building that relate to its cooling strategy and are based on the studies made by the architect Short and Associates and also by scientists at University of

Cambridge who modelled the design. A critical overview of the case study is presented in the last subchapter.

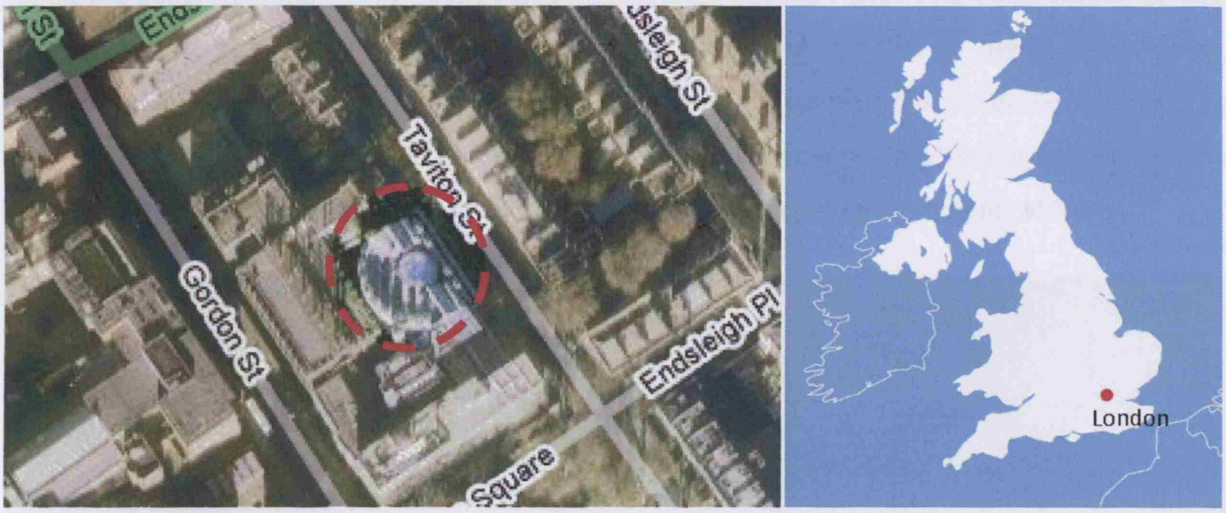


Figure 4-5. Panoramic view of SSEESS in London, UK (Source: www.googlemaps.com accessed on May 2008).

4.3.2 Psychrometric chart for the urban heat island effect of London

Major variations can be observed when comparing profile temperatures in rural areas with those in urban cities. This temperature difference varies from 1-2oK and can reach 6oK in London as illustrated in the following figure. This issue together with the increase in global temperatures due to climate change can have a significant impact in the sustainable cooling of buildings.

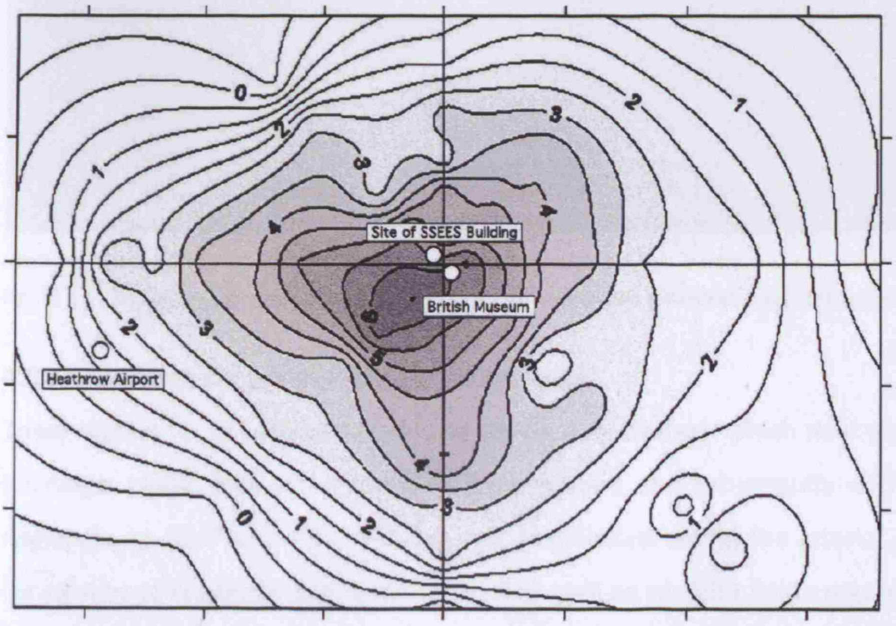


Figure 4-6. Variation in the urban heat island intensity across London on 02 August 1999 at 2:00p.m. Temperature difference (K) relative to rural reference. (Source: Short, 2004 pp. 191)

The following figure presents the psychrometric chart for the area of London, UK, considering the effect of the urban heat island. Profile temperatures, illustrated by blue points, during the cooling period are quite high, with some peaks being in the range between 30oC and 35oC. As can be seen these temperatures are within the design strategies of natural ventilation, night ventilation and thermal mass. However, there are no points in the area that is covered only by evaporative cooling; thus, evaporative cooling does not look as effective as the pre-mentioned environmental strategies for the urban heat island of London. However, it is used as the main cooling strategy for SSEES.

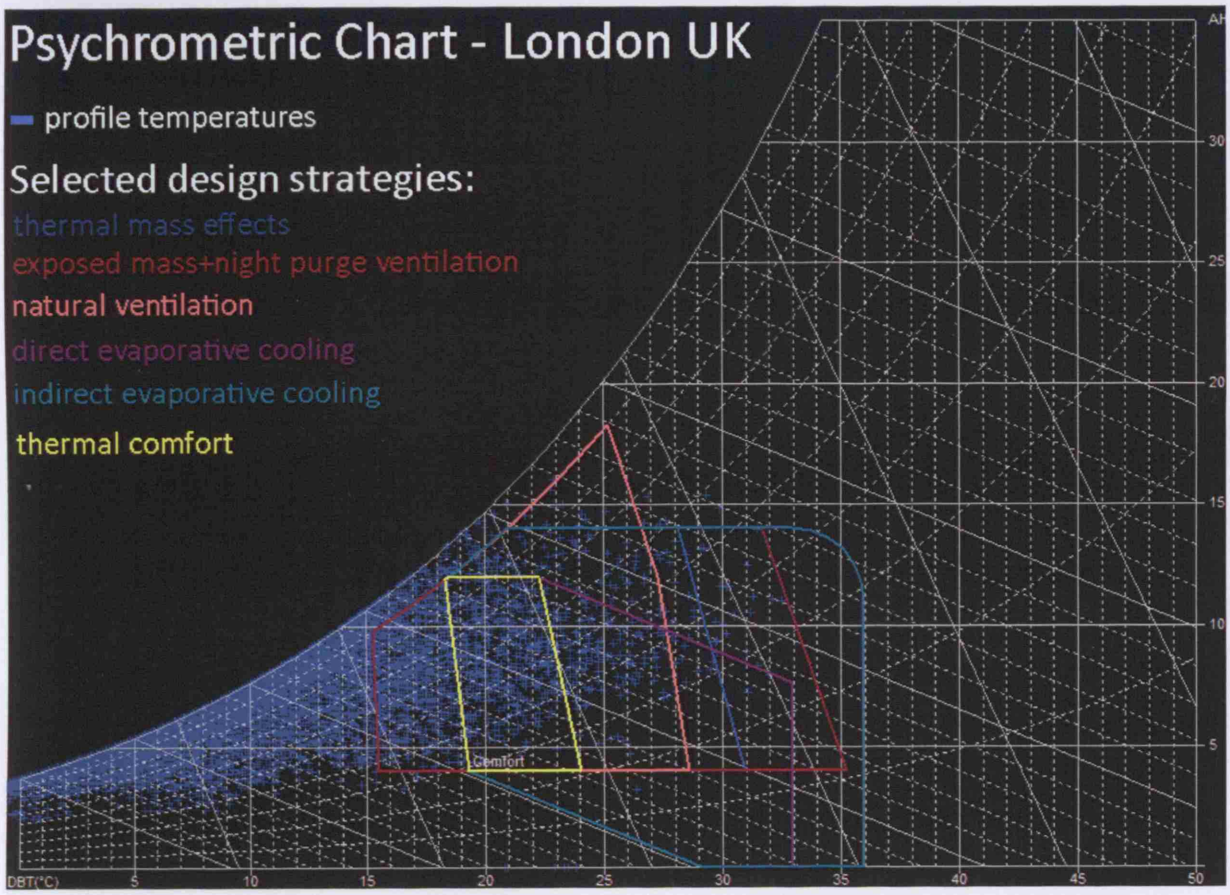


Figure 4-7. Profile temperatures, thermal comfort and favourable environmental strategies for London, UK

4.3.3 Building Design and Ventilation strategy

There were a lot of restrictions for the ventilation strategy which deal with the site and the adjacent buildings: traffic and pollution from Taviton road and propinquity with a chemistry building (see Appendix pp. 3). There were also acoustic restrictions within the interior spaces because of the need for privacy of academic and research staff as well as security limits regarding the library stock. In this way, there was a strong need for a sealed building with no opening windows at the perimeter; this lead to the use of a central light well as the core of the building (see figure 4-8); this is the key feature for the ventilation strategy. It is used basically to distribute the air within the building spaces and is attached to a plenum which connects the basement with the ground floor, which is also used for ventilation reasons. As seen in the floor plan at the appendix (pp. 4) the front spaces are separated from the rear ones for ventilation purposes; the front facade is a heavyweight brickwork wall which is used as thermal mass (appendix pp. 5). A full-height ventilation void is created behind it which isolates the internal spaces and also acts as a buffer to reduce noise and pollution from Taviton Street. It is also used as a stack for the first three storeys of the front internal spaces. At the same time roof mounted chimneys at the front facade act as exhaust stacks for the last two storeys, while perimeter stacks at the rear ventilate the spaces which are located at the back of the building. The lower ground floor is isolated with its own stack and is placed outside the building (Short et al., 2004). The whole ventilation strategy (summer period) is illustrated in detail at Figure 4-9 and its summer operation mode is presented in detail on the following ~~chapter~~ Section ('cooling strategy').

Figure4-8. The central light well at the heart of the building with the bottom hung windows.

space

4.3.4 Cooling strategy

A good low-energy solution for cooling was being sought for the SSEES building: a way of distributing the air without mechanical support led to the passive downdraught evaporative cooling. Basically, the air is inserted at the head of the light well and passes through the cooling coils, where its temperature drops (Figure 4-9). This process creates a reservoir of fresh cool air which moves physically downwards and is being distributed within the spaces through bottom-hung windows (Figure 4-8). As the air is introduced at low level in the occupied spaces (figure 4-10), it is warmed by the internal heat gains and rises to the ceiling before being exhausted through the stacks. The whole strategy relies on the driving force created by the temperature difference of air. This physical movement of air is enhanced by two design features which are implemented to optimise the buoyancy of air during summer: firstly, opening windows at the base of each stack to exhaust cool air and secondly injection of waste heat from the cooling coils below the head of each stack. Moreover, night cooling ventilation is an important contributor to the cooling strategy. During summer nights, when the subsequent day is expected to be hot, building fabric is pre-cooling by the opening of dampers which allow free night flow in the building (Lomas, 2004).

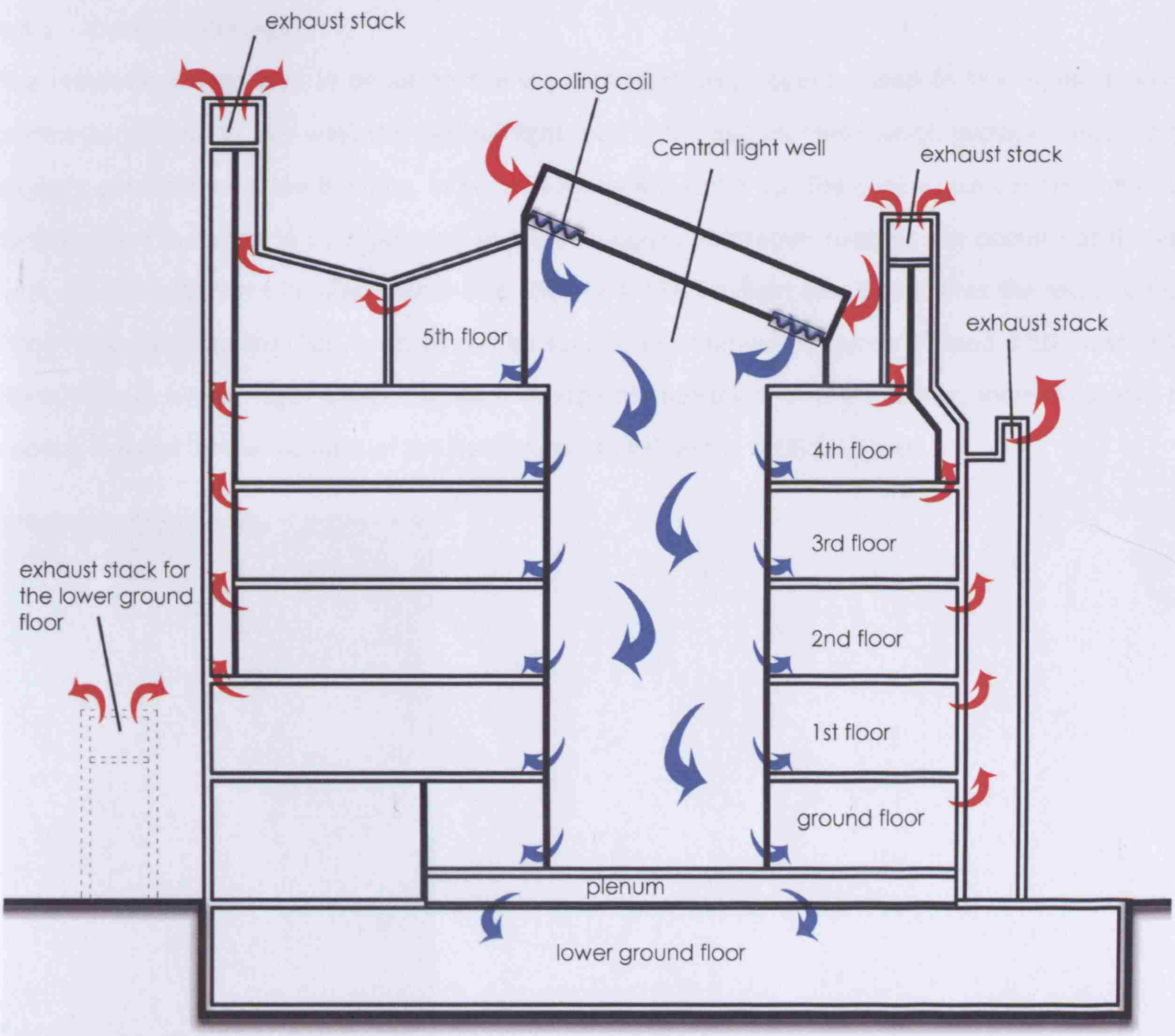


Figure4-9. Ventilation strategy during summer period for SSEESS building.

Figure 4-10. The low-level void allowing the air to be introduced in the occupied spaces.

4.3.5 Daylight strategy

The restrictions described in detail on the ventilation strategy chapter lead to the minimisation of perimeter glazing. In this way, the central light well is the key element which provides most of the daylight penetration in the building, as seen in figure 4-8 and 4-13. The cooling coils at the top of the light well are mounted in such position so that daylight penetration reaches the bottom of the light well, providing daylight in every single floor (figure 4-13). Daylight also penetrates the lower ground floor via a glazed ceiling. However, as can be seen in the photos at figures 4-8 and 4-10 most of the lights are on, which might affect the total energy consumption of the building, increasing also the cooling demand by the increase of the heat gains caused by the artificial lights.

Figure 4-11. The heavy thermal mass brickwork at the front facade.

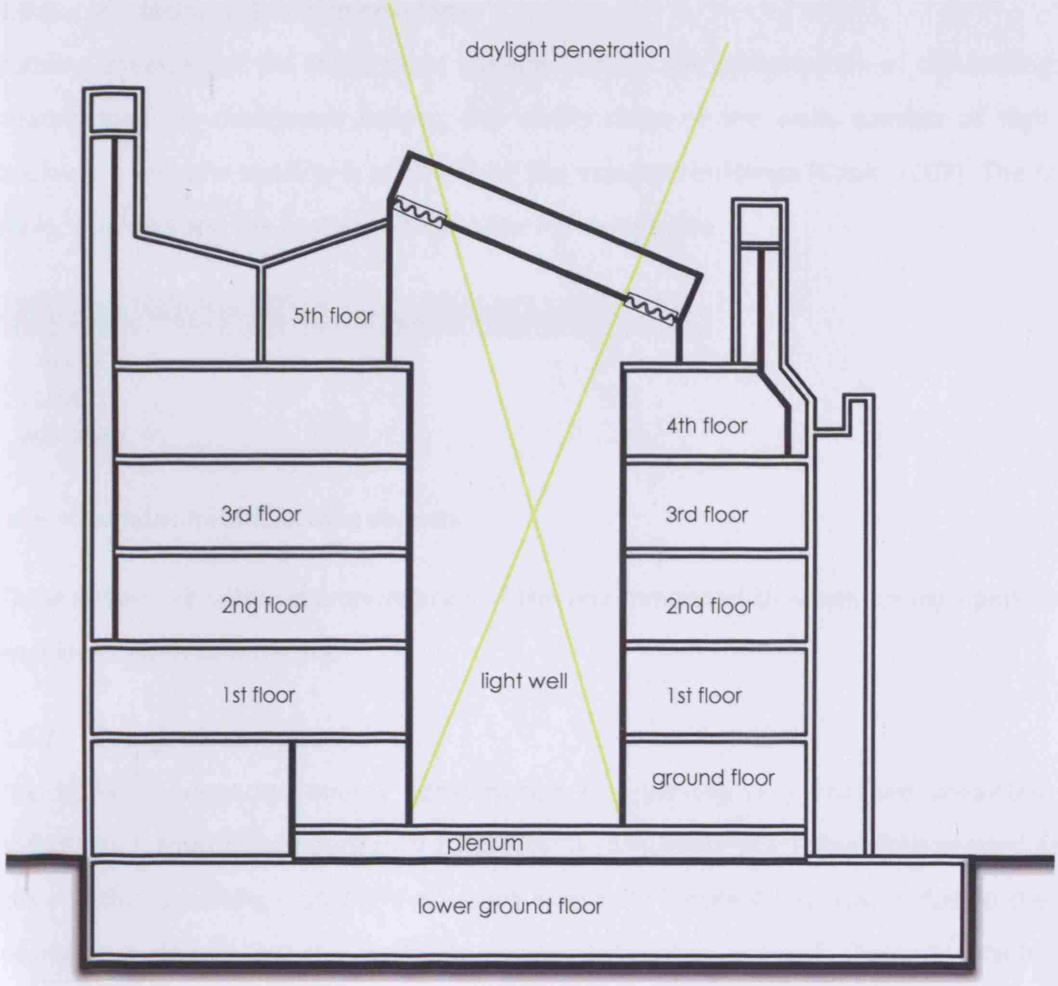


Figure 4-12. Daylight strategy for SSEES.

The front facade (figure 4-11) affects also the daylight penetration because it acts as a buffer zone for noise, pollution and ventilation reasons. In this way, it prevents the natural light to enter the building (Short et al., 2004).

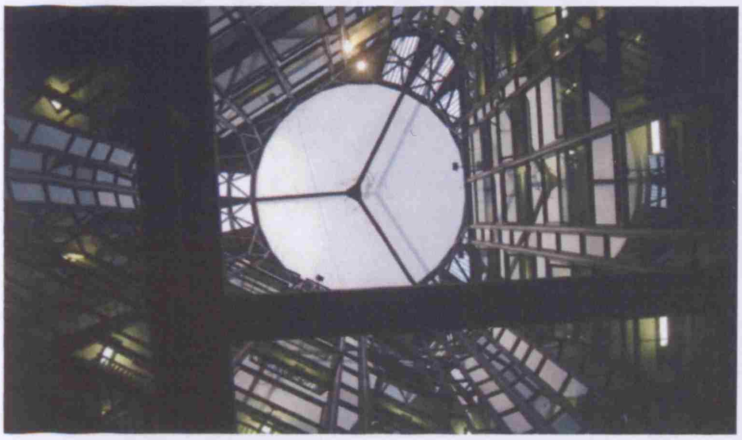


Figure 4-13. Top plan of the central light well. View from the lower ground floor.

4.3.6 Insulation of building envelope

Building envelope at the SSEES plays a major role for the minimisation of the cooling as well as the heating load. As mentioned before, the construction of the walls consists of high thermal mass brickwork. Window shading is achieved by the adjacent buildings (Cook, 2007). The U-values for the walls, windows and the roof are given at the following table.

Insulation of SSEESS building envelope (W/m^{2}K)	
walls	0.3
roof	0.2
windows	2.0

Table 4-2. U-values for SSEES building elements.

These values are within the boundaries of the recommended U-values for high performance building envelopes given at Table 3-1.

4.3.7 Energy consumption

The building's expected energy consumption is relatively very low and predicted to be around 150KWh/m^2; from this amount only 2 KWh/m^2 is consumed for cooling while around 13KWh/m^2 is for gas and the remaining -135 KWh/m^2- is for electricity (figure 4-14). This is due to the shading of the adjacent buildings which leads to very extensive use of lighting inside the building (Short et al., 2004).

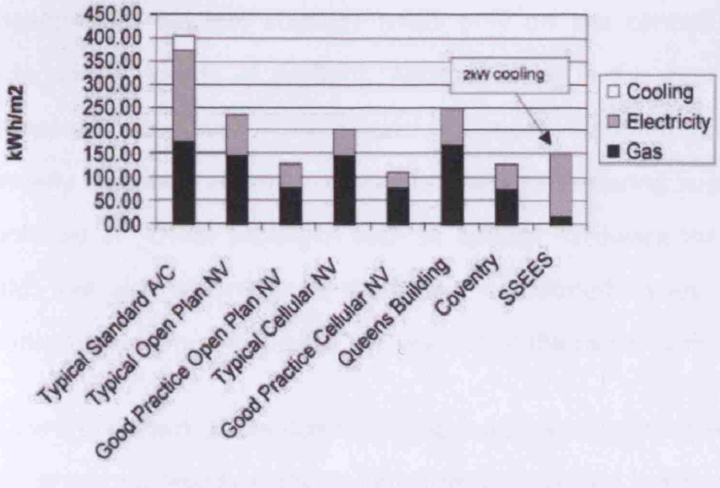


Figure 4-14. Energy consumption comparison of different buildings. (Source: Short, 2004 pp 202)

However, the annual energy consumption for the building was monitored by the BMS and was found to be 245,58KWh/m_2, lots more than the predicted energy consumption, where 121,97KWh/m_2 is for heating and 123,61KWh/m_2 is for cooling, lighting and other uses.

4.3.8 Critical overview

Designers of SSEES tried not only to design a low-energy building but basically to make the architecture a key feature of the sustainability. The sustainable cooling techniques implemented in the building are the following:

- Reduction and modulation of external heat gains (high performance building envelope)
- Reduction and modulation of internal heat gains (atrium, daylight strategy)
- Natural ventilation
- Night ventilation
- Evaporative cooling

Being the first building for the central London heat island using natural ventilation without the use of air conditioning is a big achievement. The design of the building facilitates the circulation of the cool air and in this way the use of an expensive and high energy using solution, such as HVAC system is avoided. Designers have treated effectively the design of the internal spaces together with the use of the central light well to provide sufficient amounts of fresh air and daylight.

However, the ventilation void created by the heavyweight front façade prevents sufficient daylight penetration. Daylight strategy relies only on the central light well which is not able to provide adequate amounts of daylight. Another issue is the appropriateness of the passive downdraught evaporative cooling for the climate of London. Ventilation has yet to work efficiently and occupants usually complain about excessive temperatures during summer period as well as large amounts of polluted air. Other problems such as control hardware failures and also problems relating with the BMS are also reported. All the above mentioned issues might have caused the excessive energy consumption which is double the amount of the target consumption.

A controlled test of the downdraught evaporative cooling was done in August 2007 to compare with the predicted results at the design stage but no data has come up to the journals yet. This process can help assess the cooling performance. Moreover, an occupant survey can give significant feedback regarding thermal comfort and internal condition performance of the building.

4.4 Portcullis House

Figure 4-15. General aspect of Portcullis House-Westminster.

4.4.1 Location and building characteristics.

Portcullis house is the new Parliamentary building, located opposite the Houses of Parliament and Big Ben at Westminster-London, designed by Sir Michael Hopkin's architects and partners (Figure 4-15, 4-16). It is a seven storey building that houses UK's 650 members of Parliament (MPs) in several offices, conference and committee rooms. The whole concept was to design a low-energy building which mostly takes advantage of the building fabric rather than the active mechanical and engineering services to provide good internal thermal comfort (Dix, 2000). Ove Arup and Partners worked as the Buildings Services and Facade engineering together with the architectural team. The aim was to give simple engineering solution in the design stage resulting in saving significant amounts of energy as opposed to a naturally ventilated building. The building started its operation in autumn 2000.

This study relies on the previous studies accomplished by the architectural and engineering team who designed Portcullis House. Various issues concerning buildings performance have been analysed to come up to a critical overview in the last subchapter.

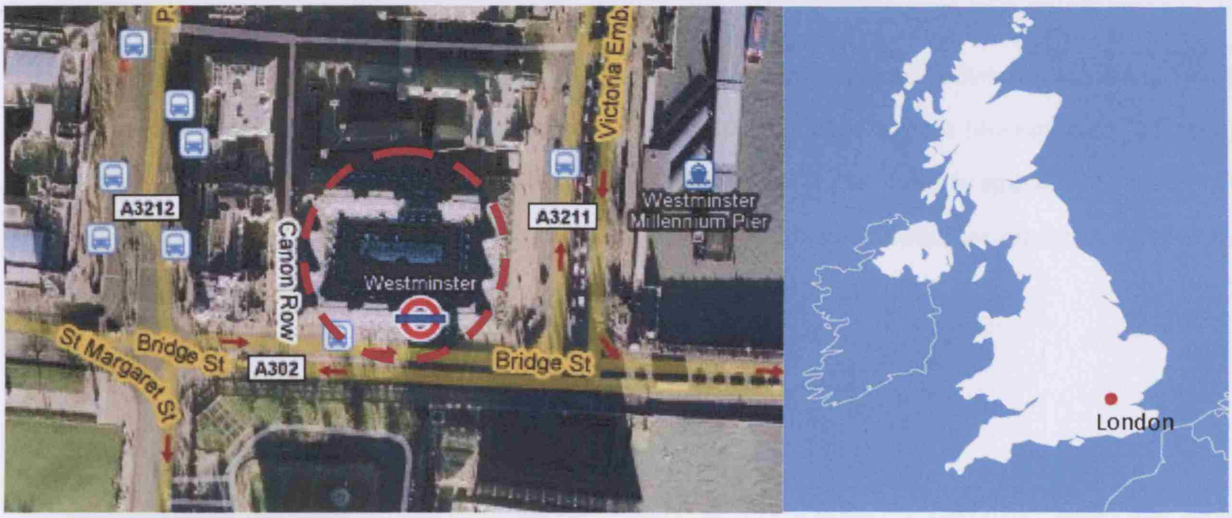


Figure 4-16. Panoramic view of Portcullis House in London, UK (Source: maps.google.com accessed on May 2008).

4.4.2 Psychrometric chart and environmental strategies

The weather tool analysis of the profile temperatures, previously presented, gives natural ventilation with thermal mass and night ventilation. In Portcullis House night ventilation is used together with high thermal mass. However, natural ventilation is avoided with the use of a displacement ventilation system.

4.4.3 Building envelope's performance

The most important element in Portcullis House is the integration of building services in the architecture of the building. The facade is a highly active construction which consists of triple plane glazing with argon filled and low emissivity coating and also has a ventilative cavity, which serves for the distribution ducts (figure 4-17). The facade has a high thermal resistance, which results in blocking the heat from outside to inside and vice versa; in this way, interior heat is kept indoors. As seen in the following table the U-value of the external facade is a mere 0.27, while walls are within the recommended values for high performance building envelopes, given in table 3-1 (Bunn, 2000).

Insulation of Portculis House building envelope (W/m^{2}K)	
walls	0.27
roof	1.0
floor	1.0
external façade	0.27
triple bay window	1.89

Table 4-3. Insulation values for Portcullis House

4.4.4 Daylight strategy

Daylight is considered significantly for the sustainability of Portcullis House. Louvers are used to block the lower sun angles during winter while higher sun angles during summer are blocked by a light self; glass prism surfaces on the self act as a reflector of daylight upon the interior space. This results in doubling the daylight, especially in north facing offices, where adjacent buildings obstruct a sky view (Dix, 2000). The daylight strategy is illustrated at figure 4-17.

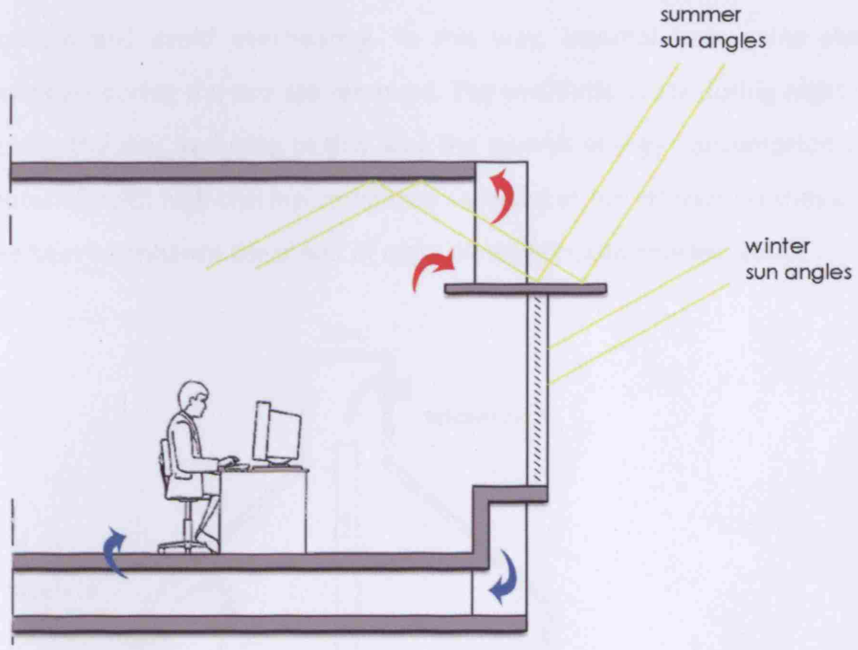


Figure 4-17. Ventilative facade and daylight strategy for Portcullis House

4.4.5 Ventilation Strategy

The building uses a low velocity state-of-the-art displacement ventilation system, instead of air-conditioning system, which saves energy because it is assisted by buoyancy action. The plan is organised around a central courtyard (Appendix pp. 6). Along the building perimeter 14 chimney stacks ventilate the building; air is drawn at the base of the chimneys and is distributed through the sandwiched duct system, integrated at the facade (figure 4-18). Each floor has a ventilation plenum at the floor level where air circulates before being introduced in the occupied spaces. Air is exhausted at ceiling level and distributed through the duct system at the facade to the chimneys (Bunn, 2000). No recirculation of exhaust air takes place but the system supports heat recovery, through a roof mounted rotary hygroscopic 'thermal wheel'; the recovered heat comprises solar heat captured at the facade, internal heat from occupants and electric devices and also heat emitted by the radiators. A cross section showing the building services and the ventilation strategy is presented in Appendix pp. 7.

4.4.6 Cooling strategy

Two main strategies are being used to cool the building. Ground cooling takes place with two boreholes used to pump water from a ground depth of 120-150m. When the outside temperature goes above 19oC, ground water of around 14oC is pumped and is used via a heat exchanger to cool the ventilation air (figure 4-18). In this way, a 19oC temperature of fresh air is achieved; this air is used to ventilate and condition the occupied spaces through the displacement ventilation system (Dix, 2000). Additionally, night ventilation is used, when needed, to enhance the cooling strategy of the building and avoid overheating. In this way, internal heat gains absorbed by the thermal mass materials during the day are removed. The ventilation rate during night ventilation is half of that used during the day, reducing in this way the overall energy consumption of the building. Thermal mass materials with high thermal resistance are used at the interior finishes and also at the ceiling to absorb the heat to enhance the effect of night ventilation (Bottomley, 2000),.

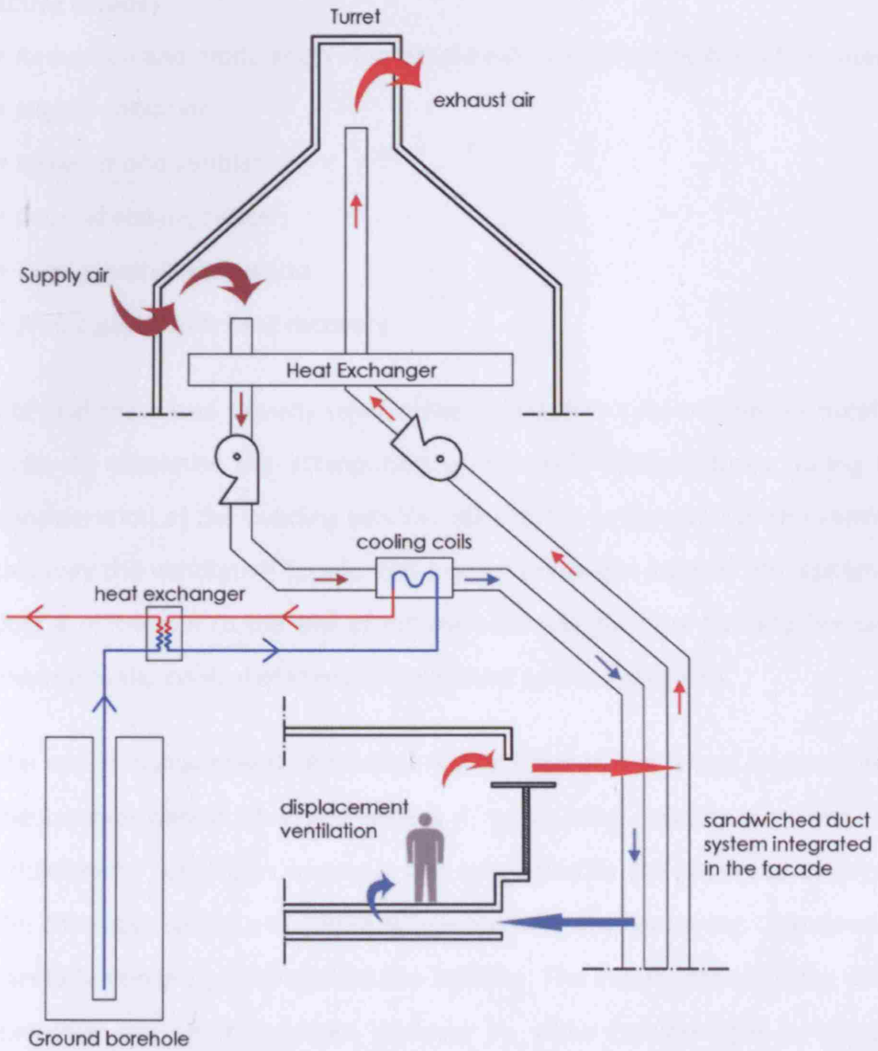


Figure4-18. Cooling strategy during summer for Portcullis House.

4.4.7 Energy targets

The energy targets given by the services and facade engineering consultant company Ove Arup and Partners for the building were 141KWh/m^2 (Dix, 2000), which is far below the typical naturally ventilated example 2 from ECON 19 presented in figure 4-2. However, actual numbers for the building's energy performance is not yet released. The facilities department of the building was unable to give any data from the BMS for security reasons.

4.4.8 Critical overview

The designers of Portcullis House relied on the fabric of the building to temper its internal conditions and provide thermal comfort. Sustainable cooling techniques were detected in the building and are the following:

- Reduction and modulation of external heat gains (high performance building envelope, climate-active facade)
- Reduction and modulation of internal heat gains (atrium, daylight strategy)
- Night ventilation
- Mixed-mode ventilation
- Ground cooling (water)
- Displacement ventilation
- Free cooling with heat recovery

Thermal mass was cleverly used in the ceiling and interior finishes together with night ventilation in order to maximise the attenuation of the peak temperatures during the hot period. A thorough consideration of the building services lead to the integration of the ventilation ducts in the facade; in this way the ventilative facade was one of the major keys of the sustainability. However, this facade puts a restriction to the use of natural ventilation in the building because it is sealed; this fact also minimises the control of internal conditions by the occupants.

The use of displacement ventilation was inevitable, but it was assisted by ground borehole cooling for the summer period. This method has a high cooling capacity providing cool air in the interior spaces. Additionally, ventilation system is also supported by the heat recovery system mounted in the head of the chimneys, which provides a supplementary energy saving. Moreover, designers have considered carefully daylight penetration in the building. The incorporation of the ducts in the facade restricts the excessive use of transparent surfaces to allow natural light to penetrate the occupied spaces.

However, the use of the light self maximises the daylight penetration, even in winter period when the luminance is low.

Readings from the BMS as well as feedback from the occupants can help identify weaknesses in the thermal performance. Routine monitoring can measure buildings energy consumption and compare with the target consumption given by the designers. A good co-operation of the facilities department with the design team should be the baseline to improve the buildings thermal performance. Occupants' satisfaction survey can give significant advice on how the system works and whether or not it provides satisfactory thermal comfort conditions.

4.5 Swiss Re Tower.

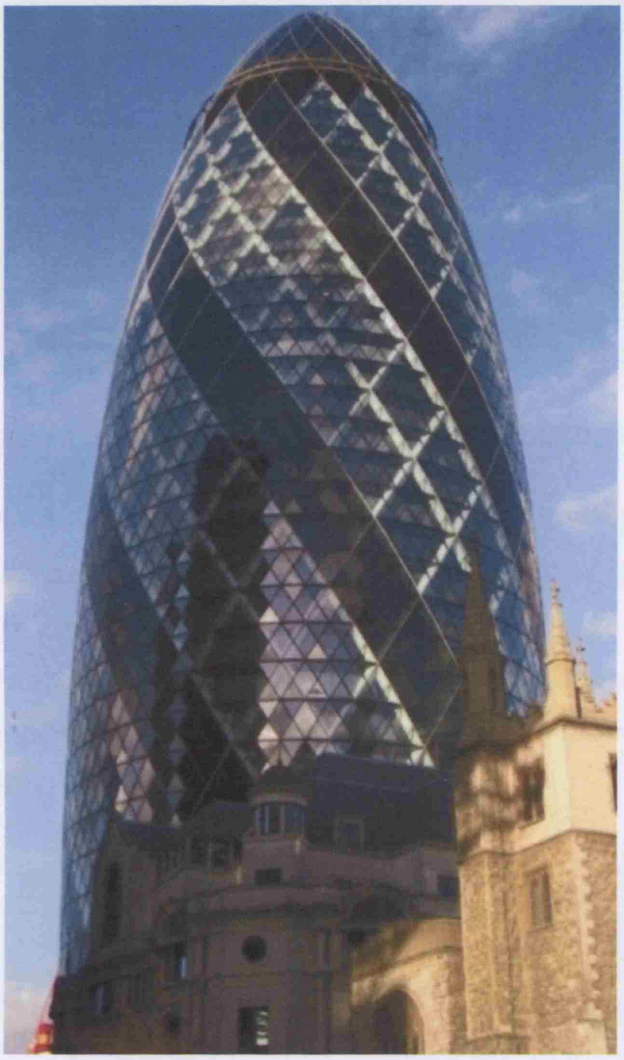


Figure4-19. Swiss Re Tower.

4.5.1 Location and main building attributes.

Swiss Re Tower (figure 4-19) is a 40 storey office building of 180m tall, designed by Foster and Partners; it is located at 30 St Mary Axe in the centre of London (figure 4-20). It is the first environmental skyscraper in the heart of the city, whose cone like shape makes it a landmark. The concept was to design a building which takes the most advantage of the integration of structure and building services into the architectural design. In this way, the basic element in the environmental strategy was the facade of the Swiss Re Tower, which is an active ventilative one. The building is equipped with mixed-mode ventilation; natural ventilation assists the mechanical air-conditioning system and reduces the energy demand. Construction started in 2001 and first occupation took place in 2004 (Powel, 2006).

The following study relies in the design studies made from Foster and Partners Architects and the facade engineering team of Ove Arup and Partners. The chapter ends with a critical overview of the systems used to cool the building.

4.5.2 Psychrometric chart and environmental strategies.

External conditions of the urban heat island of London were discussed in previous chapter. Instead of the environmental strategies recommended from the psychrometric chart given in figure 4-7, Swiss Re Tower uses a mixed-mode system, with natural ventilation and air-conditioning system to temper its internal conditions.

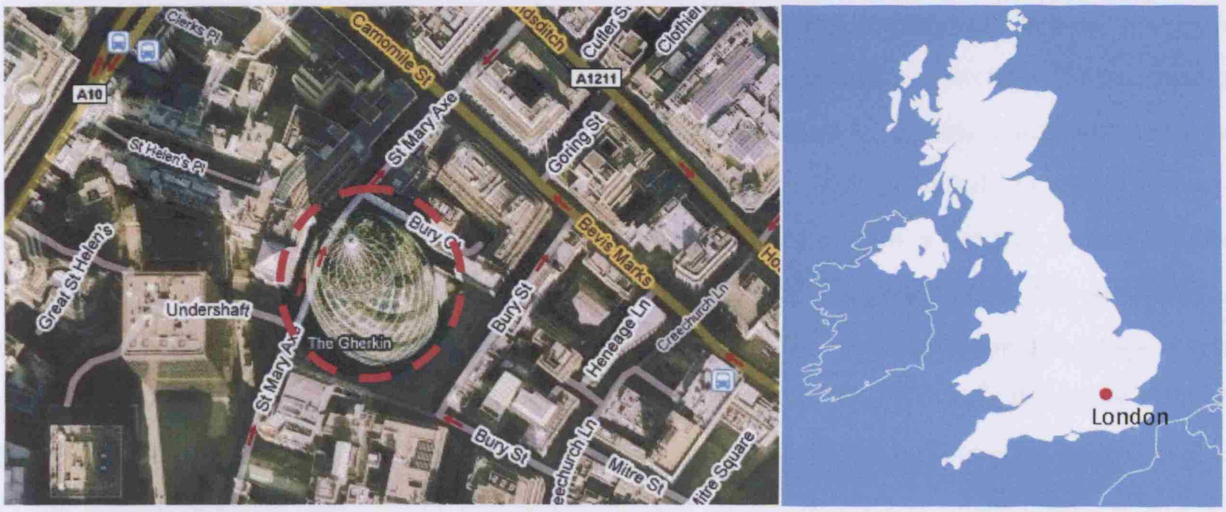


Figure 4-20. Panoramic view of Swiss Re Tower in London, UK (Source: maps.google.com accessed on May 2008).

4.5.3 From Building Design to Ventilation Strategy

The tower's standing shape is aerodynamic due to the different diameters of each foorplate, with the 17th level having the biggest one. The entrance level accommodates retail use, while offices are located in the levels above; last levels are separated having no atriums and accommodate plant rooms, restaurants and bars (more details are presented in the drawings on the appendix, pp. 8 and 9).

Figure4-21. Atriums creating spirals of darker glass at the elevation (left). Aspect from the inside (centre) (Source: Powell 2006 pp.79). Openable windows in the atria (right) (Source: Powell 2006 pp. 81)

The plan is organised through a central core, where the staircases and elevators are located, while the offices are spread at the perimeter. Each floorplate has six triangular atriums at the perimeter, which develop a spiral stripe made of darker glass at the elevation (figure 4-21); this is achieved because each floorplate is twisted 5o relative to the floor below it (Pearson, 2002). The atriums act as the lungs of the building used to ventilate naturally the building. The circular plan is the key feature for the ventilation strategy. This shape, because of its smaller surface, –approximately 25% less than a rectangular one- copes with less heat losses and less solar gains. The most significant advantage of this shape is that it deals well with the wind, preventing turbulences (figure 4-22); air enters through monitorised opening windows in the atria (figure 4-21), which act also as buffers preventing draughts in the offices. However, the overall ventilation strategy of the building is mixed-mode, where air conditioning cannot be avoided because of the building height and the site location (Powel, 2006).

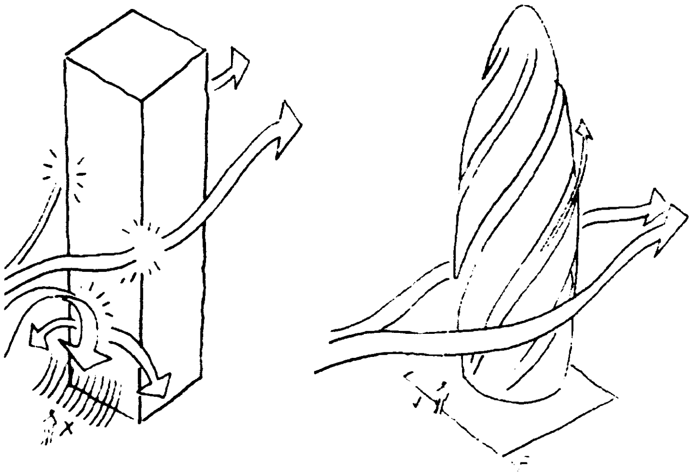


Figure 4-22. The advantages of the conelike shape together with the spiral shape of the atriums (left) (Source: Powell 2006, pp 98).

4.5.4 Facade design

The facade is the most important element of the environmental strategy of the building. It comprises of a triple skin facade with a double glazed outer skin, followed by a 1.0-1.5m gap (Figure 4-23). The inner skin consists of a single glazing pane, a ventilative gap and a layer of aluminium louvers. The exhaust air circulates through the facade's gap and removes the heat coming from the inner glazed skin of the offices and also the heat absorbed by the blinds; in this way, the percentage of solar transmission is a mere 15%, while the U-value of the facade is reduced to 0.8W/m^2/K, when the air circulates through the gap (Kitson, 2003). Therefore, the overall cooling load needed for the office space is reduced significantly.

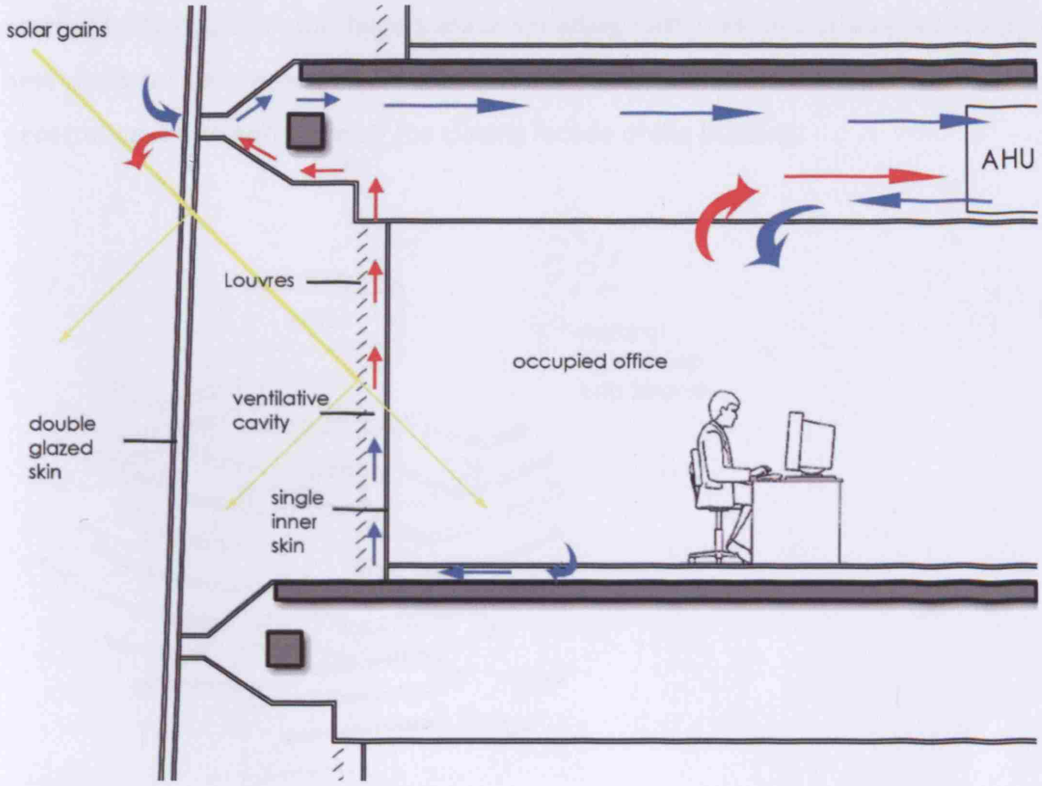


Figure4-23. Cooling strategy (summer) for Swiss Re Tower.

4.5.5 Cooling Strategy

Apart from the ventilative facade, which plays a major role in cooling the building, air conditioning is also installed. Mixed-mode system which also uses natural ventilation for cooling reasons is used for 40% of the year (Pearson, 2002). The whole concept of the air conditioning installation is based on a decentralised system which serves each floor separately. Air is introduced through grilles at the facade at ceiling level (Figure 4-23), is passed through the air handling unit before being introduced in the occupied space at high-ceiling level; fan coil units are used to cool the air. Part of this cool air is then extracted through floor outlets and passes through the ventilative facade duct, cooling the glass and the blinds before being extracted outside. Most of the heavy plant, like chillers and tanks are located at the basement of the building while the cooling towers are located at 35th level (appendix pp. 8 and 9). Energy efficiency is achieved by the use of the waste heat from condenser water. Waste heat is also used from the ventilated facade and is provided to the thermal wheels mounted at the AHU (Kitson, 2003).

4.5.6 Daylight Strategy

Daylight strategy for Swiss Re Tower relies on the whole concept of the design of the building. As mentioned before, the floorplates are twisted clockwise to each other so that the triangular atriums created by the voids in the fingers make spiralling balconies. In this way, as illustrated in figure 4-24 best views are succeeded and natural light penetrates deep into the space (Powell, 2006). The daylight penetration is also enhanced by the glazing facade of the building.

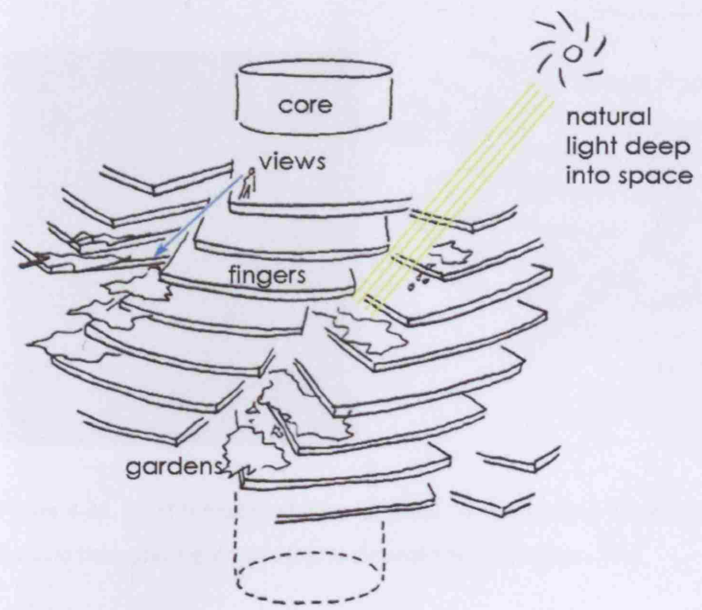


Figure 4-24. Sketch showing daylight strategy for Swiss Re Tower (Source Powell 2006, pp.78).

4.5.7 Thermal modelling-energy consumption

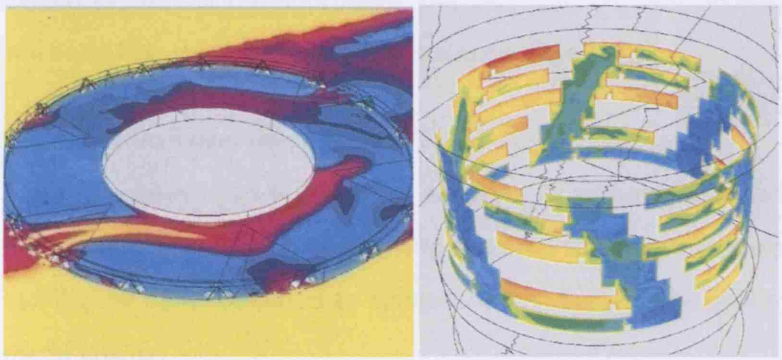


Figure 4-25. CFD modelling for Swiss Re Tower (Source: Powell, 2006 pp. 80)

CDF modelling (figure 4-25) together with dynamic thermal modelling was used to test the buildings thermal performance analysing all aspects of the design; the ventilative facade, the natural ventilation and the lightwells. CFD was also recently used to compare different plan solutions including open plan offices instead of cellular ones. The predicted energy consumption of the building is 150kWh/m^2 and is very close to a naturally ventilated open plan office building presented previously in figure 4-2. Wind tunnel testing (figure 4-26) was also applied to take the most advantage of the prevailing south-west winds for the natural ventilation strategy.

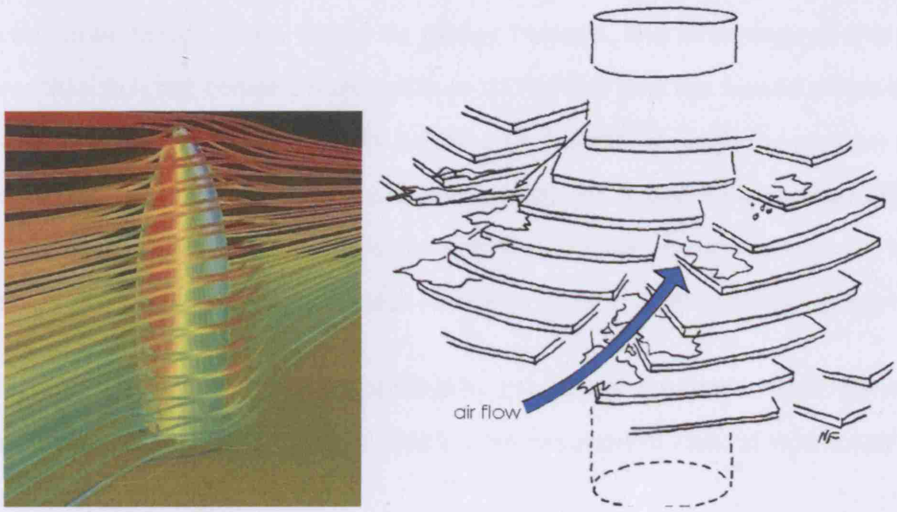


Figure 4-26. Wind tunnel modelling for Swiss Re Tower (left) (Source: Powell, 2006 pp. 80) Sketch showing the intended air flow on the spiralling atriums (right) (Source Powell 2006, pp.78).

As the air flows around the building it creates positive pressure on the windward side and negative pressures on the sides of the building; this embraces the perfect driving force for cross flow ventilation (Kitson, 2003). This pressure variation enhances the natural ventilation. Foster first suggested the anti-clockwise twist of the floorplates, but then this changed to clockwise to take the most advantage of the prevailing south-west winds blowing in the area.

4.5.8 Critical overview

Swiss Re Tower is an outstanding example of sustainable skyscraper. Designers succeeded in taking the most advantage of energy saving methods to achieve a decrease in the energy consumption of the building by half, compared to similar towers. Sustainable cooling techniques used in the building are the following:

- Reduction and modulation of external heat gains (high performance building envelope, climate-active facade)
- Reduction and modulation of internal heat gains (atrium, daylight strategy)
- Natural ventilation
- Mixed-mode ventilation
- free cooling with heat recovery

The most important element in the energy saving methods used is the integration of elements on the design of the tower; six shafts that are used to ventilate naturally the building together with the incorporation of building services in the design of the building and the implementation of the active ventilative facade, from where air passes through. The advantage of this combination is that natural ventilation is not compromised because of the fact that the facade of the building is not totally sealed; this gives the opportunity to the building to 'breath' through the atriums and also makes the internal environment more interesting, providing balconies to the atriums where occupants can seat and enjoy the views. However, the use a decentralised HVAC system could not been avoided, because the building is one of the largest ones and needs to cope with high heat gains.

Daylight strategy is not compromised by the use of the facade void, used for ventilation and cooling purposes -as was in the case of SSEES-. Optimisation of natural light takes place through the spiralling atriums and the glazed facade.

Although the building is in operations for 4 years energy consumption of the building is not known because BMS readings are not yet released to the public for security reasons. Moreover, an occupant satisfaction survey has not yet been conducted. This can give the designers a good understanding of the buildings thermal performance.

4.6 National Trust Headquarters - Heelis Building

Figure4-27. Main-south facade of Heelis building.

4.6.1 Site location and main building features.

Heelis Building (figure 4-27) is the new building of National Trust Headquarters located on the site of Great Western Railway Works in Swindon (figure 4-28). It is a two-storey construction of 7000m^2 which accommodates mainly open plan offices, located on the first floor, together with offices, a shop, a public cafe-restaurant and a membership recruitment area on the ground floor (see Appendix pp. 10). The key feature on the design was sustainability which was achieved by setting high quality benchmarks. The building was designed by Feilden Clegg Bradley architects with the co-operation of Max Fordham as M&E consulting. It is one of the fewest deep plan office buildings which uses almost entirely natural ventilation to keep it cool and also relies on natural daylight (Randall, 2006). The construction was completed in 2005 and the building has been operating for two years.

This study refers to the sustainable cooling techniques applied in the building and is based on the design study by the architects and environmental engineers. It concludes with a critical overview of the techniques.

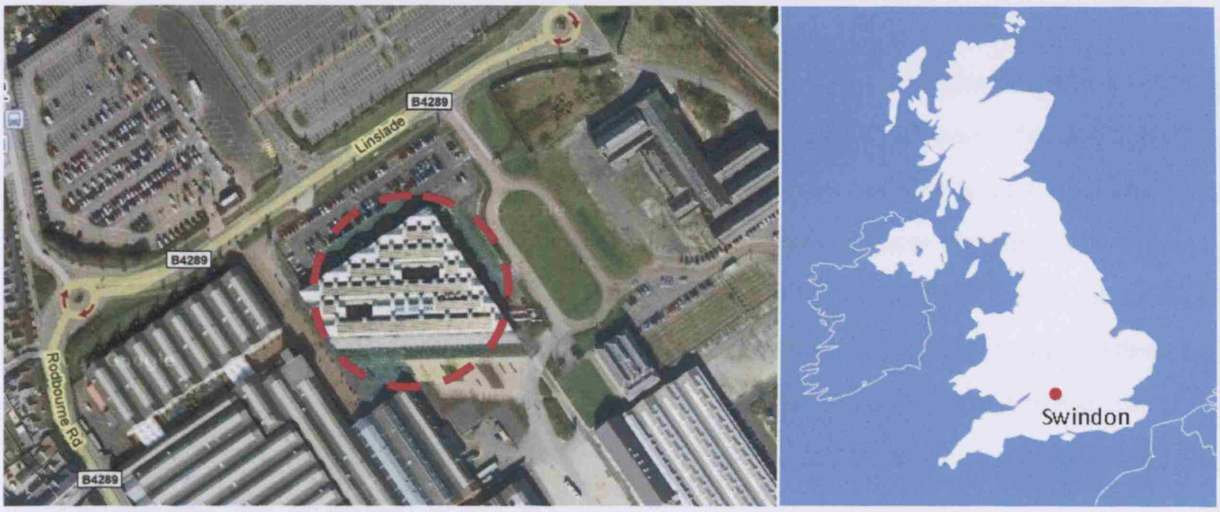


Figure 4-28. Panoramic view of Heelis Building in Swindon, UK

4.6.2 Psychrometric chart and environmental strategies.

Bristol is the most proximate city to Swindon and its weather file was available to use it on 'Weather Tool' software. In this way, assuming that the weather profile temperatures are similar to Swindon they are presented in figure 4-29. As can be seen some temperatures are outside the thermal comfort during the cooling period; the proposed environmental strategies are the same as in Cardiff: natural ventilation with thermal mass and night ventilation; these strategies are implemented to Heelis building.

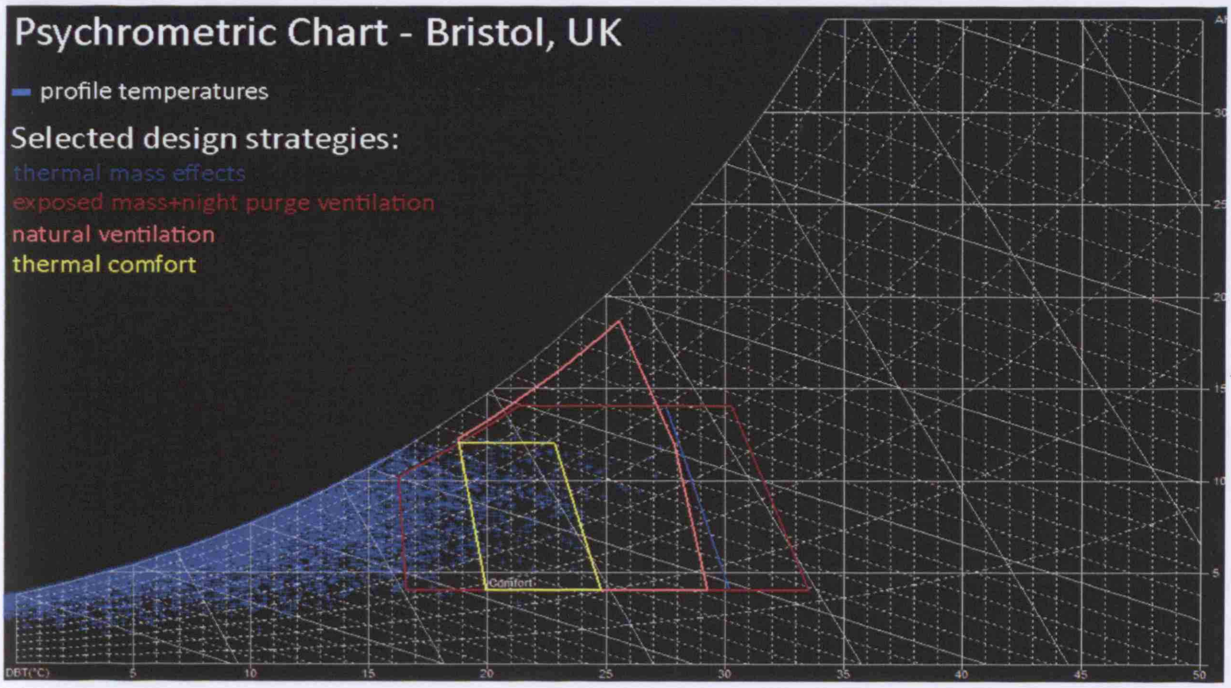


figure 4-29. Profile temperatures, thermal comfort and favourable environmental strategies for Bristol, UK.

4.6.3 Natural ventilation

The whole design of the building relies on natural ventilation strategy. The plan is organised so that the main facade is due south and that the double-pitched roof faces south-north (Koralek, 2005). In this way, an east-west axis organises the building plan with two main courtyards located in the middle (see Appendix pp 10); they act as lungs to provide natural ventilation even at the most central areas of the building. Air is introduced at the perimeter by high level automatically controlled windows and large door sized ventilation panels (figure 4-31) at the main-south facade. However, all windows have the facility to open manually; this gives the occupants the satisfaction of controlling the indoor conditions. Air is exhausted via roof ventilators called 'snouts' (figure 4-32). Some of the exhaust outlets have mechanical support which is used in very hot, still internal conditions. The whole ventilation strategy is illustrated in two sections presented in figure 4-30. Natural ventilation is achieved by stack effect but is also enhanced by external wind pressure (Spring, 2005).

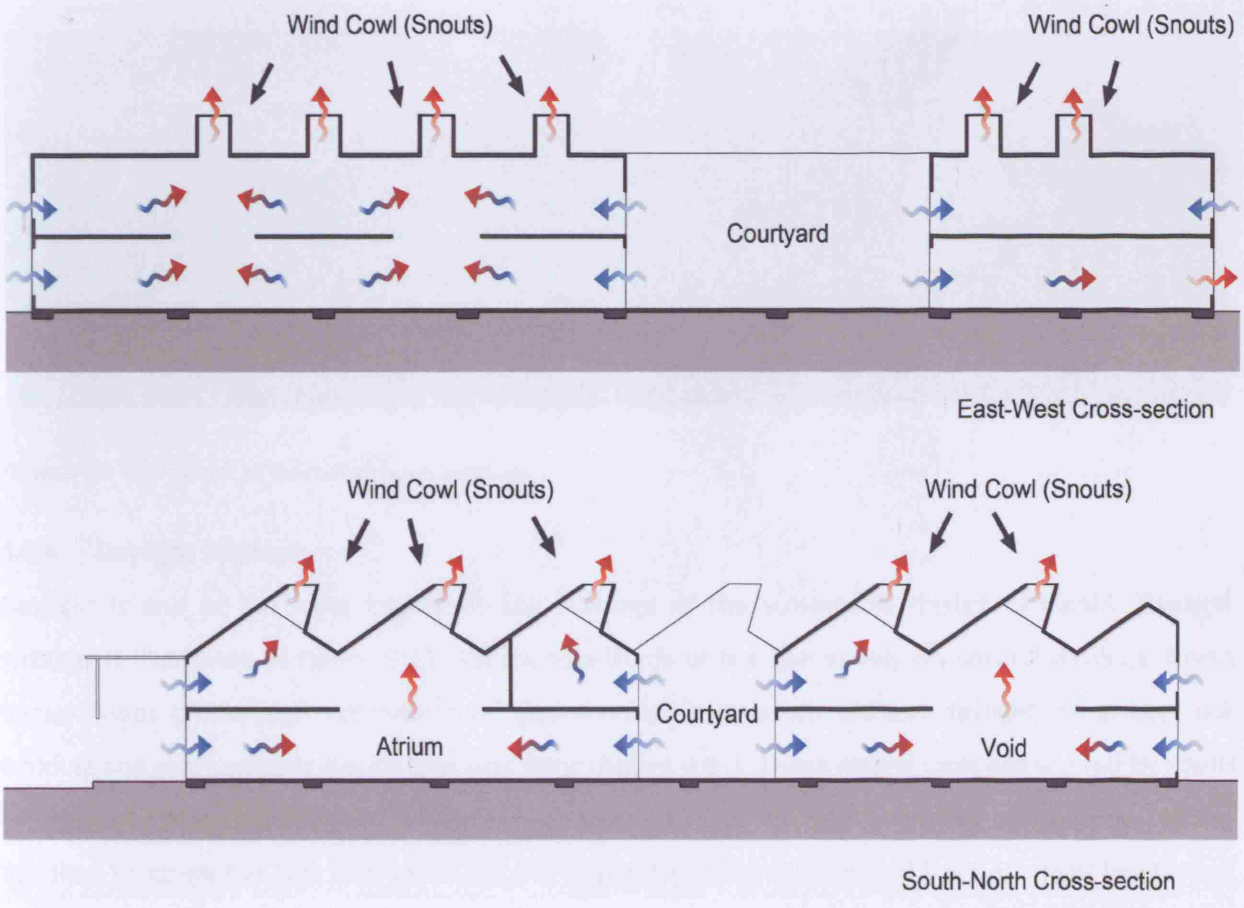


Figure4-30. Ventilation strategy for Heelis building.

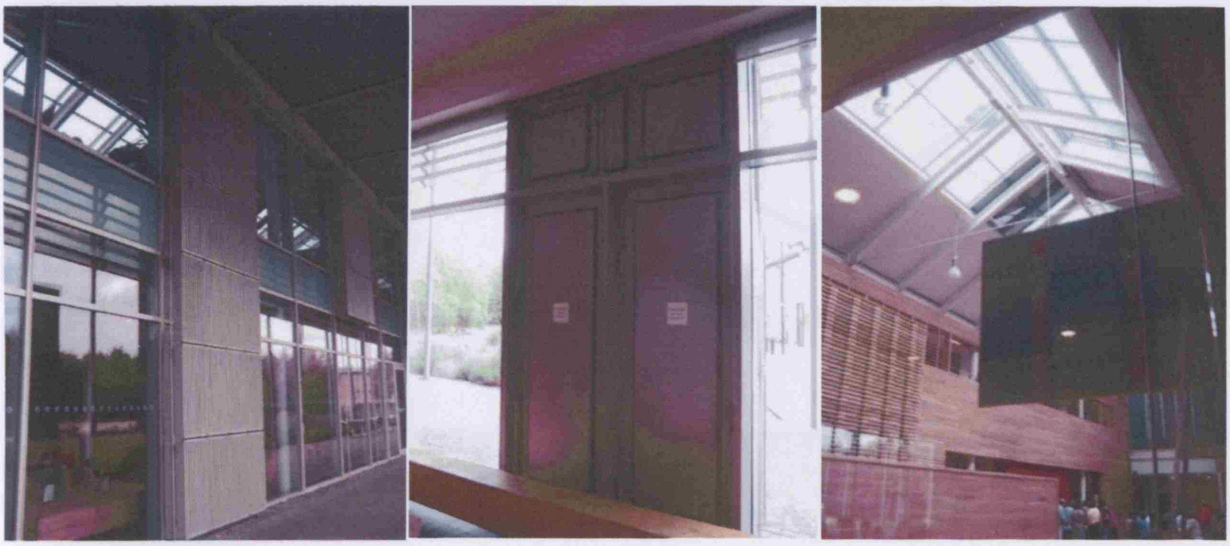


Figure 4-31. Large door-sized ventilation panels as they look from the exterior and the interior (left-centre). Daylight penetration at Heelis Buildng (right).

Figure 4-32. The 'snouts' at the roof of Heelis building.

4.6.4 Daylight strategy

Daylight is one of the most important key features of the sustainable design of Heelis. Daylight strategy is illustrated at Figure 4-33. Almost two-thirds of the spaces rely on natural daylight. North facing slopes of the roof accommodate glazed units, from which indirect daylight penetrates the building and reaches both ground and first floor (Figure 4-31). These glazed units are shaded by south facing photovoltaic installations, which provide nearly 15% of the total electricity consumption of the building. Voids on the first floor allow natural daylight to reach the ground floor. Daylight factors are more than 5% in a great percentage of the interior spaces; on the first floor daylight factors is between 10% and 15% and in this way lights are rarely on. However, on the ground floor these factors are less, starting from 10% and reaching a mere 1% in few 'dark' spaces below the mezzanines that usually have their lights on (Randall, 2006). Daylight penetration is also enhanced by the two courtyards.

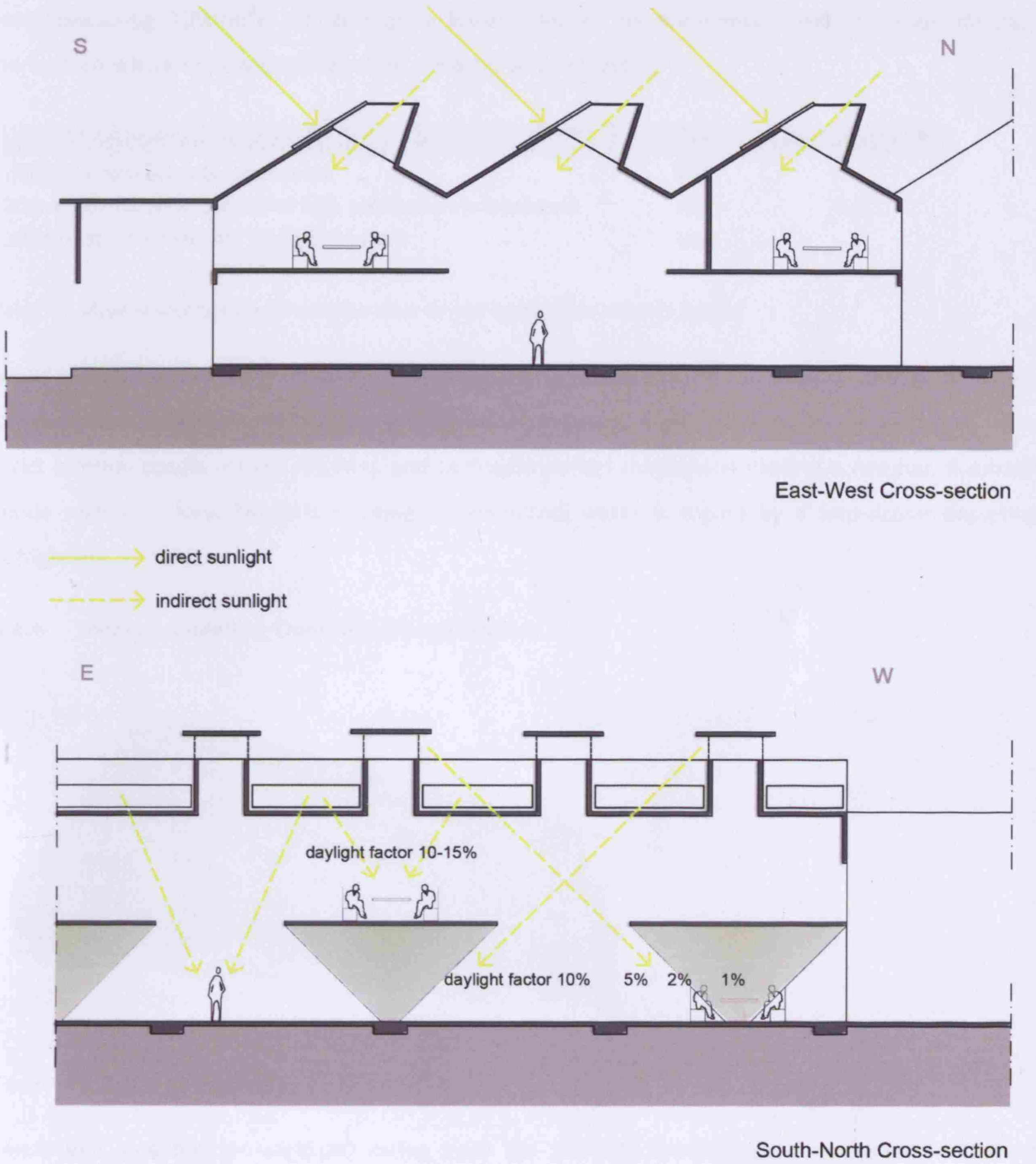


Figure 4-33. Daylight strategy for Heelis building.

4.6.5 Cooling strategy – envelope performance

The whole strategy for cooling relies in night ventilation. The 442mm thick walls, made of concrete block work and external brickwork, together with the roof which is made of 80mm thick exposed precast concrete panels have very high insulation values and high thermal resistances. The following table gives the material description for the walls at Heelis. As can be seen the insulation value is very low, measuring 0.2W/m^{2}K, which is quite lower than the recommended insulation value for high performance building envelopes given in table 3-1 (Gilbert, 2007).

material description for walls	mm	U-Value(W/m2K)
thick internal concrete block work	140	
200mm cavity with 150mm of high performance insulation	200	**0.2**
102mm of thick external facing brickwork	102	

Table 4-4. Material description and insulation value for wall construction at Heelis building

Walls and roof act as the thermal mass of the building, which absorbs the internal heat gains during the day and purges them during the night. However, in spaces with high internal heat gains and more strict internal conditions like meeting and computer rooms mechanical cooling is needed. A mixed-mode system of local fan coils is being implemented; water is cooled by a zero-ozone depleting refrigerant.

4.6.6 Thermal modelling-Operational performance

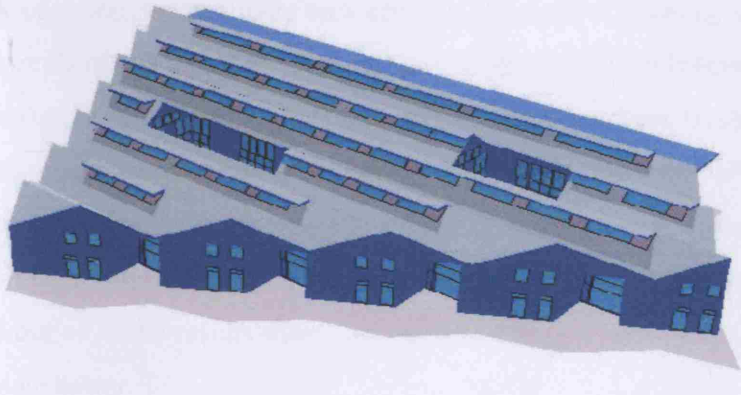


Figure 4-34. Thermal model for Heelis building. (Source:

Heelis was awarded an 'excelent' rating from the BREEAM environmental assessment. Thermal modelling has been accomplished by Max Fordham consulting engineers to assess its thermal behaviour. Designers have set high targets, expecting to achieve around 75kWh/m^2 (Morris, 2007).

Readings from the BMS give significant feedback about the buildings real performance. Figure 4-36 presents the readings; targets given by CIBSE (CIBSE Guide A, 2006) are achieved: dry resultant temperature does not exceed 25oC for more than 5% of working hours and 28oC for more than 1% (Nevill, 2007). This outlines the fact that Heelis building is performing as expected and that these targets can be improved and meet an even greater margin by next years of building's performance.

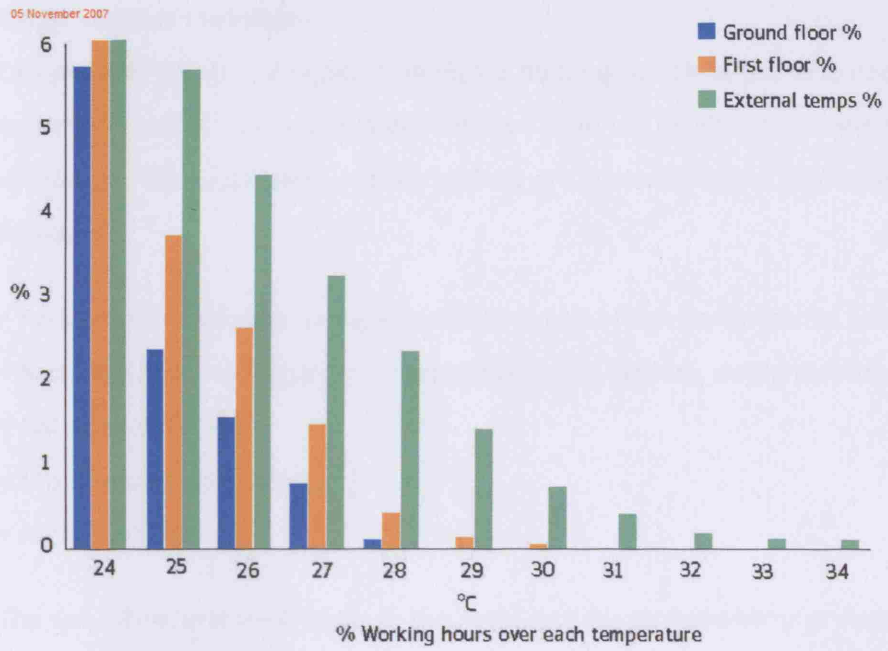


Figure 4-35. Summary of annual internal temperatures for the year 2006. (Source: Nevill, 2007 pp.35)

4.6.7 Occupant survey

A post-occupancy survey was done by consultant Building Use Studies in November 2006, with a sample of 242 members of the staff (Morris, 2007). The following figure presents the results; the scale is from 1-unsatisfactory to 7-satisfactory, the blue lines illustrate the UK benchmarks and the green diamonds present the mean values. As can be seen most of the findings are very close to the blue lines, except for the temperature and the air in summer and also the noise, where the findings are a bit below the UK benchmarks. However, the overall comfort is very satisfactory, recording more than 5 out of 7. The results show that Heelis building is performing very well and has some potential to be even better.

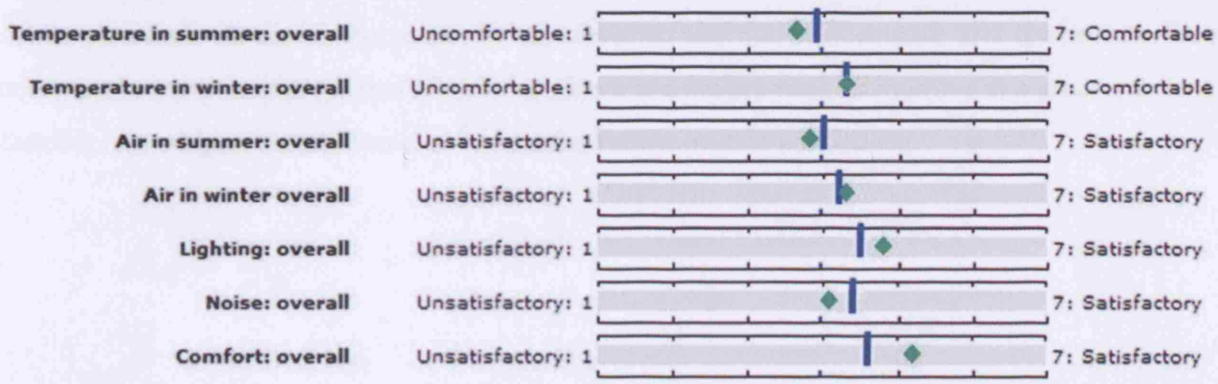


Figure 4-36. Occupant satisfaction survey for Heelis Building (Source Nevill, 2007 pp 37)

4.6.8 Critical overview

Designers of Heelis managed to design a building which is the first deep plan office building using natural ventilation and which is yet believed from the results to perform very well in terms of internal conditions. The sustainable cooling techniques implemented in the building form and design are the following:

- Reduction and modulation of external heat gains (high performance building envelope)
- Reduction and modulation of internal heat gains (atrium, daylight strategy)
- Natural ventilation
- Mixed-mode ventilation
- Night ventilation

The use of natural ventilation is the main key for sustainability at Heelis. Night ventilation is used together with the high thermal mass materials to alleviate the peaks during the hot period. The fact that there is a minimization on the use of mechanical support makes the building more flexible and adaptive to the desired internal conditions. Mixed-mode ventilation is used only in demanding areas and demanding weather periods.

Daylight strategy is also much appreciated by the designers, where 2/3 of the building are totally daylit. Although Heelis is a deep plan office building with big compact footprint, in most of the spaces adequate daylight penetrates the interior; two atriums create two 'holes' in the plan enhancing both daylight penetration and air introduction into the occupied spaces. Moreover, the monitoring of the building as well as the occupant satisfaction survey have shown that the building is performing as expected and both identified in which ways it can be improved.

Several studies have been made for Heelis which helped to assess its thermal performance. It is a good building example where a comparison of the designed thermal performance and the real has been accomplished with numerous ways. However, there are always ways to improve in a greater extent a building regarding its thermal conditions by using robust routine monitoring.

4.7 National Assembly for Wales - The Senedd

Figure4-37. General aspect of the National Assembly for Wales-The Senedd

4.7.1 Location and main building characteristics

National Assembly for Wales (figure 4-38) is a three-storey building, located on a prominent waterfront site in Cardiff Bay (figure 4-37); it is designed by Richard Rogers and Partners. Architects and engineers were working together from the earliest stages of the building design, which relies on sustainability in the built environment. The plan is organised through the heart of the building, which is called Debating Chambre (Siambr) and accommodates the meetings of 60 Assembly members. It is located on the ground floor together with committee, office and meeting rooms (detailed floor plans are presented on the Appendix pp 11,12,13). The main entrance area with the reception on the first floor and the cafe and seating areas on the second floor are open to the public. The building was finished and started operating in 2005 (Smith, 2001).

This study was made according to previous studies by the architects and the environmental studies by BDSP. A critical overview is presented at the end of the chapter.

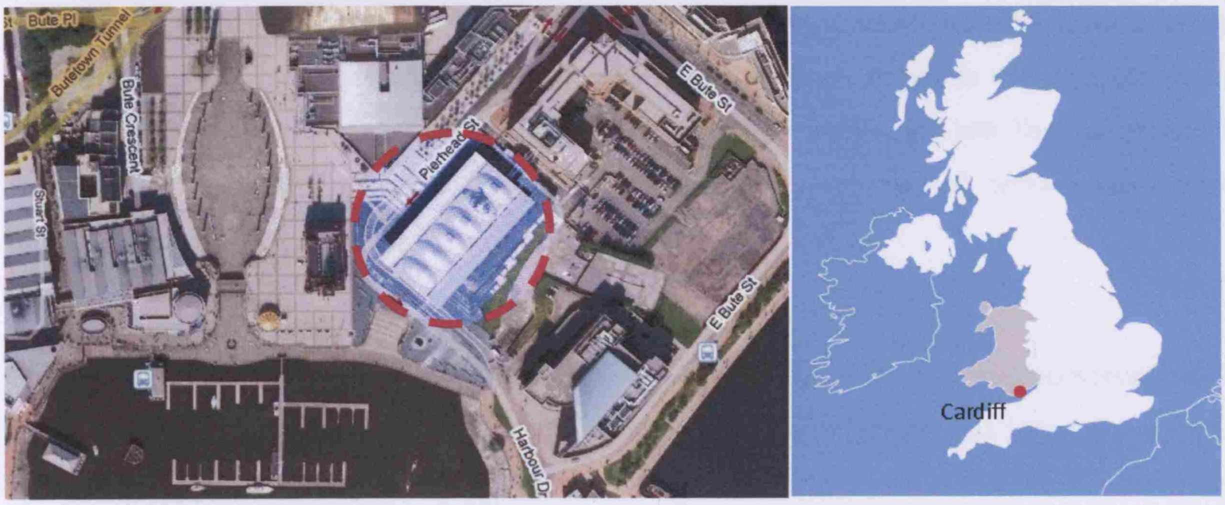


Figure 4-38. Panoramic view of The National Assembly for Wales in Cardiff

4.7.2 Psychrometric chart - environmental strategies.

The temperature profiles for Cardiff in Wales were plotted and can be seen in the following psychrometric chart (figure 4-39). As can be seen most of the temperatures are lower than the thermal comfort and thus heating load is more predominant than cooling load.

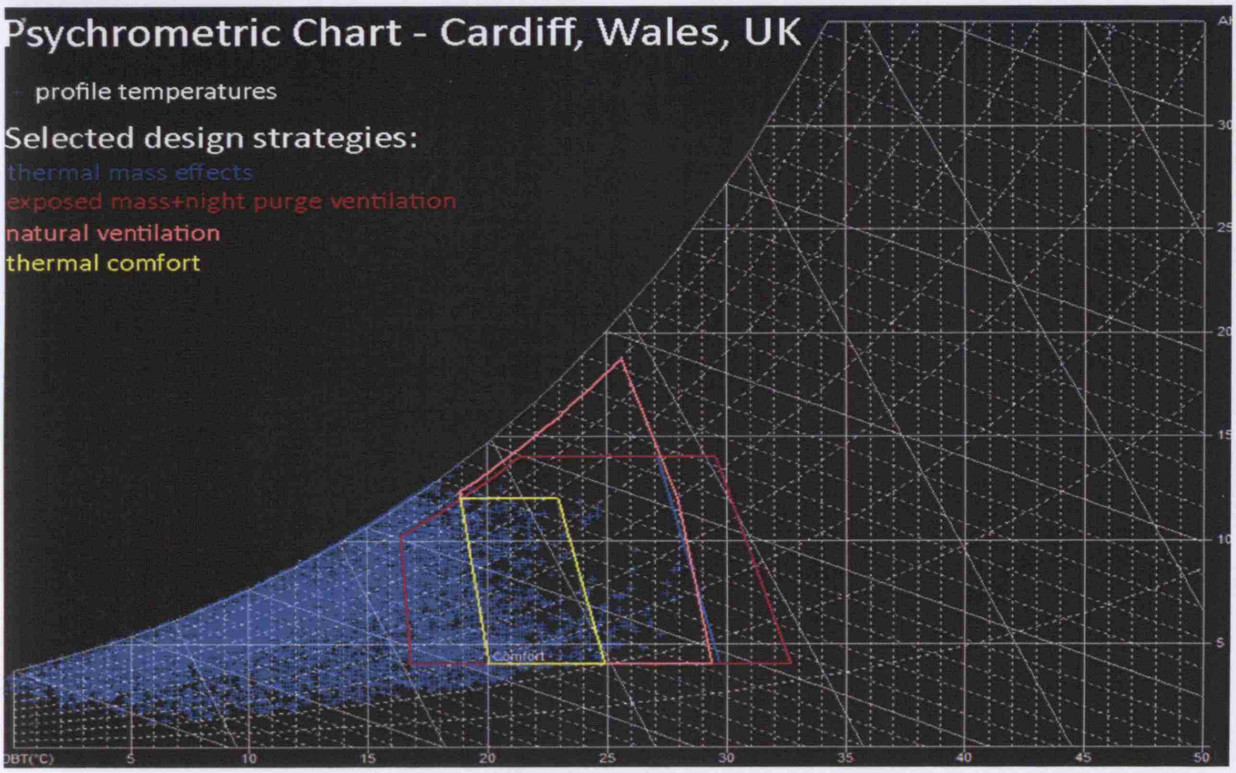


figure 4-39. Profile temperatures, thermal comfort and favourable design strategies for Cardiff, Wales, UK

However, there are some temperatures that may cause overheating and can be avoided by the application of the mentioned design strategies; the suggested design strategies in the psychrometric chart (figure 4-39) comprise mainly natural ventilation and night ventilation with thermal mass. The Senedd relies on natural ventilation but also uses mechanical support to temper the internal conditions in some spaces.

4.7.3 Natural ventilation

The predominant mode operating in the building is natural ventilation. The key environmental feature is the roof cowl, which is used for ventilation purposes and for maximising daylight penetration within the building via the lantern. Public spaces are entirely naturally ventilated with the use of windows on the glazed facades of the building; single sided and cross ventilation is used for these spaces (figure 4-40). Important feature on the strategy comprise also the use of thermal mass materials such as concrete and slate, which help temper the internal conditions (Cinqualibre, 2007). The debating chamber and the committee rooms have an air conditioning back-up system, which is used when there are higher internal heat gains or when stricter internal conditions are needed. The air is inserted through inlets in the floor and is exhausted through windows in the committee rooms or through the roof funnel in the Siambr (Figure 4-41 and 4-42).

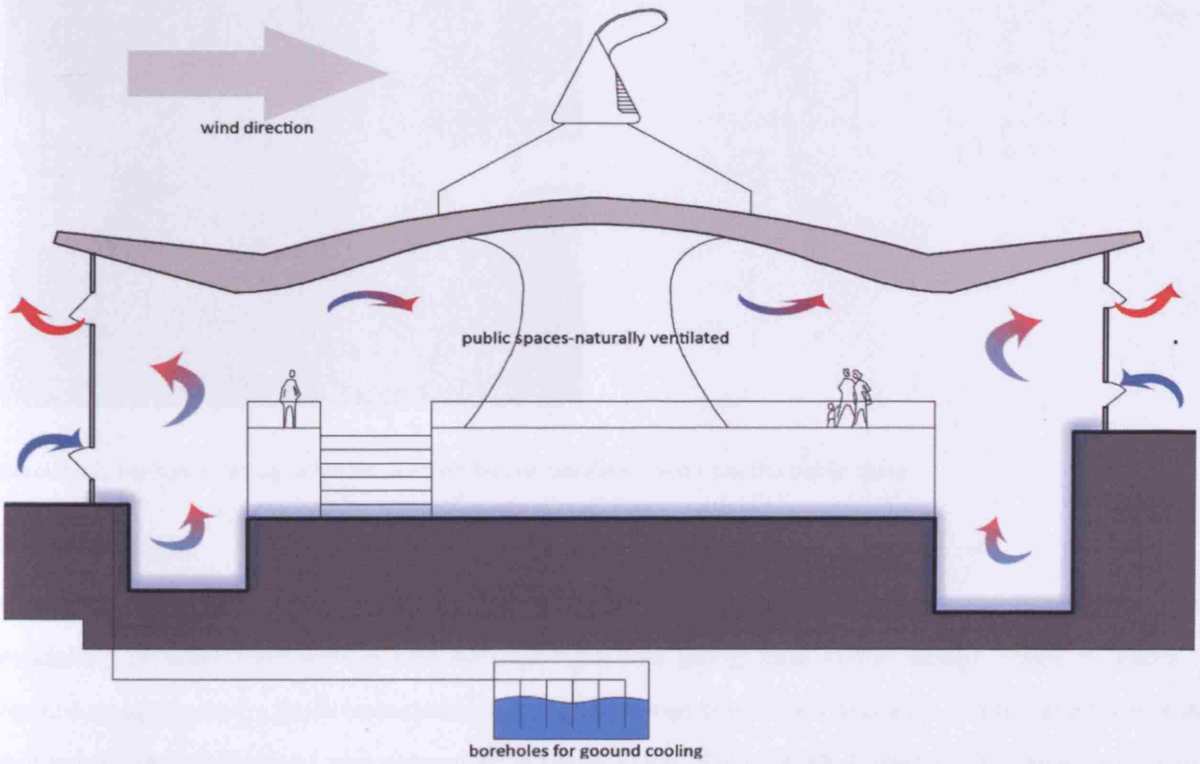


Figure 4-40. Natural ventilation strategy together with ground cooling for public spaces in The Senedd.

The wind cowl located at the top of the Siambr is 6m high and has the possibility to rotate according to the prevailing wind (Figure 4-41); in this way, a negative pressure is created at the leeward side of it, where outlets are located to exhaust the warm air from the building and thus reduce the energy requirements for air conditioning.

Figure 4-41. The wind cowl at the roof top of the Senedd (Source: Correnza, 2006, pp 9).

Figure4-42. The funnel acting as the stack effect for the Siambr viewed from the public space

4.7.4 Daylight

One of the most important elements of sustainability is the daylight entering the Senedd. Extensive modelling of solar penetration and natural light was being held in the design stage to allow the maximum amounts for both low winter and high summer sun angles and also at different times a day. A combination of artificial and natural light takes place. Figure 4-43 illustrates the daylight strategy. Natural light enters the building through the lantern at the roof top funnel; this comprises of a conical mirror which reflects the light within the building. Daylight penetration is also optimised through the glass facades by mirrors on all four elevations of the building and also glazed roof light in the office and committee rooms.

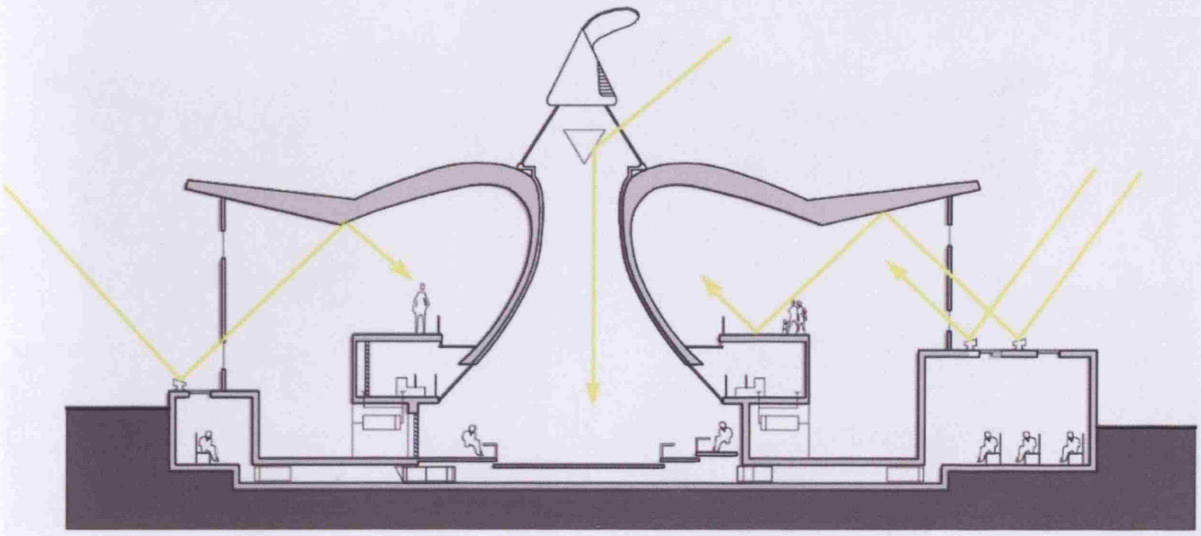


Figure 4-43. Daylight strategy for the National Assembly for Wales.

4.7.5 Cooling Strategy

The spaces in the Senedd have diversity in terms of environmental control; the minimum control is in the public spaces, which are naturally ventilated, while the offices, the committee rooms and the debating chamber at the heart of the building are highly controlled; mixed mode ventilation is used for these spaces (figure 4-44). The latter spaces, as mentioned before, have a backup air conditioning system, which draws air from the plenum up to the conditioned spaces. Ground earth heat exchangers are used for cooling; 27 boreholes are buried into the ground and supply with cool water via ground source heat pumps (Correnza et al., 2006). Water circulates through a matrix of small pipes underneath the slate floor and absorbs the heat from the building. Then, the heat is deposited to the ground and the process is resumed, resulting in reducing the cooling load demand. The system is also used as under floor heating during winter. The whole system reduces the size of conventional boilers and chillers; GSHP operate two to three times more efficiently than conventional systems. Therefore, significant energy savings are achieved. The engineers believe that the building will use no more than 50% of a conventional building operating in the same location. The whole summer ventilation strategy for various areas in the Senedd is presented in detail in figure 4-44.

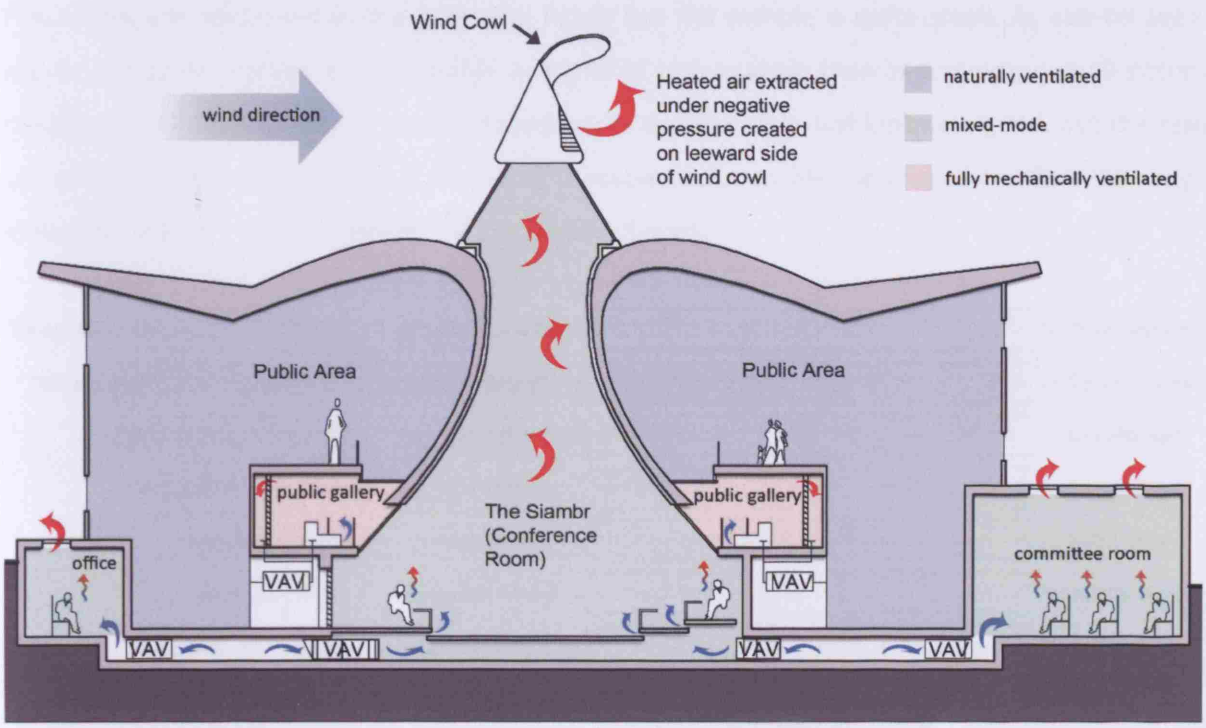


Figure4-44. Summer ventilation strategy for the Senedd.

4.7.6 Energy consumption and CO_2 emissions.

The Senedd was awarded the BREEAM 'excellent rating' for the environmental features which are incorporated in the design and contribute to the buildings low energy consumption; these include the boreholes, grey water for cycling and also the extensive use of natural ventilation and natural light. The building's energy targets are at the scale of 75KWh/m^2 which is much below the best practice target of 130 KWh/m^2 (Smith, 2001). The CO_2 emissions also are predicted to be low especially because of the use of the biomass boiler used to heat the building but also because of the use of the ground source boreholes used to cool and also heat the building.

4.7.7 Occupant survey.

An occupant survey was done in cooperation with the facilities department of the building. 21 people who work in the building were given questionnaires and were asked if they are satisfied in terms of thermal comfort. All the people who were asked were members of the staff and not committee members, so none of the answers refers to the Siambr. The format used is the same with the one presented for the occupant satisfaction survey for Heelis building. However, one of the restrictions in this survey is that the sample is too small.

The results are presented in the following figure but the sample is quite small. As can be seen in winter occupants feel more comfortable in terms of temperature than in summer; overall occupant satisfaction in terms of both air and temperature in summer does not look very good, but the results are still good recording 3.1 and 3.68 out of 7 respectively. As for the overall comfort the range is around 4.1 out of 7, which is still below the UK benchmark.

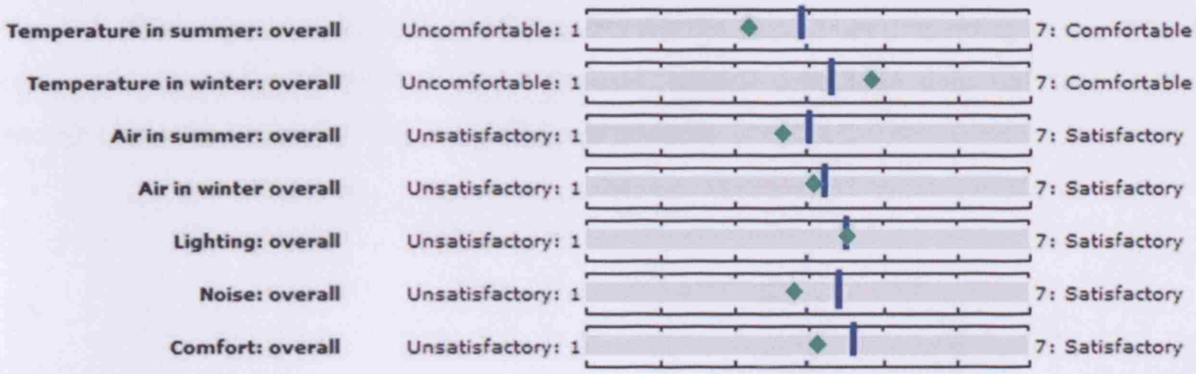


Figure 4-45. Occupant survey for the Senned.

Results show that there is much potential for the building to perform better. Monitoring of internal temperatures by the BMS can also help improve the overall comfort and the satisfaction of the occupants.

4.7.8 Critical overview

The National Assembly for Wales is designed to be environmentally friendly. Sustainability relies on several features such as the roof which describe the design of the building. Sustainable cooling techniques that are applied to the Senedd comprise the following:

- Reduction and modulation of external heat gains (high performance building envelope)
- Reduction and modulation of internal heat gains (daylight strategy)
- Natural ventilation
- Mixed-mode ventilation
- Ground cooling (water)
- Displacement ventilation

Designers have considered lots of design features to maximise the energy saving in the building. The expected reduction on the running costs goes up to 30-50%. The main attribute for the cooling strategy is the roof cowl, which funnels air into the debating chamber. Natural ventilation is the main ventilation strategy, which is only compromised by the use of displacement ventilation in spaces where better controls of internal conditions are required and where occupancy patterns are denser. Another major key of the sustainability is the daylight strategy. Designers took the most advantage of the daylight using reflecting surfaces to maximise it in the interior spaces.

Occupant's survey showed that the building is not performing as expected, especially during summer. Energy consumption is expected to be too low, which might be feasible. However, internal conditions in public spaces seem to be compromised; they are not the desired ones regarding air quality and air temperature according to the occupants' answers. Natural ventilation does not seem sufficient enough to provide the appropriate indoor thermal comfort.

5. Discussion of Analysis

5.1 General

Although all the case study buildings are located in the UK three of them are found in London whereas one is in Swindon and one is in Cardiff. All of them comprise buildings with office use or relevant uses. Four of them are currently built and started their operation within the last four years, except of the Portcullis House which started operating in 2000. They encompass large buildings with floor areas ranging from 4075m^2 to 47950m^2 and a variety of storeys, from 1 storey (Heelis) to 39 storeys building (Swiss RE). The key elements that address the sustainability are defined in the design stage and in every case study are mostly related with the ventilation strategy.

type\building	SSEES	Portculis House	Swiss RE	Heelis	NAW
Location	London, UK	London, UK	London, UK	Swindon, UK	Cardiff, UK
Building Type	Academic	Office	Office	Office	Civic
Building Size (floors)*	LG+G+5storeys	G+5storeys	LG+G+39storeys	G+1storey	LG+G+1storey
Footprint size	31.5m*27.0m	3830m^2	1100m^2	3500m^2	49.0m*74.0m
Floor Area (m2)	4075	23000	47950	7000	7100
Sustainability Key for cooling	seasonal operation mode of ventilation strategy	building fabric and ventilative façade	active ventilative façade	natural ventilation and night ventilation	natural ventilation and ground cooling
First Operation	2005	2000	2004	2006	2005

*LG=lower ground floor, G=ground floor

Table 5-1. General information for the case study buildings

Different aspects of sustainability were sought from the designers in each case. SSEES uses seasonal operational mode for the ventilation strategy which makes it more adaptive to the external climate. Swiss Re and Portcullis House rely on the active ventilative facade; the latter one is using also its fabric to attenuate its internal conditions. Finally, Heelis and NAW both achieve high standards of sustainability by using natural ventilation together with excessive daylight strategies implemented in the design.

5.2 Adaptation with climate-design considerations

The design of the buildings seems to be one of the most important stages. This involves a great number of parameters that should be taken much into consideration. The location of the site of each building together with the climate both address the techniques adopted. All the buildings are situated in the UK where the climate is temperate; temperatures usually do not go below -5°C during winter and rarely rise over 25^are°C during summer. However, SSEES, Portcullis House and Swiss Re are located within the urban heat island of London which is described by milder winters and warmer summers. In this way, other aspects of cooling should be considered by the designers because in urban areas natural ventilation limits the opportunity of sufficient cooling. In the case of Swiss Re natural ventilation is assisted by the support of HVAC system while in Portcullis House the facade is totally sealed using HVAC system which is supported by a ground cooling system. However, the designers of SSEES took the challenge to use natural ventilation with downdraught evaporative cooling, a really old technique, which is not suitable for London's dry climate. On the other side, Heelis and NAW which are located in sub urban areas both rely on natural ventilation with the former using night cooling and the latter using mechanical support. Thermal mass materials such as floor, ceilings and interior finishes are also implemented for all case studies except Swiss Re; they assist in the cooling strategies of each building helping to temper their internal temperatures.

It should be noted that the building design can address the cooling strategy adopted in a building and can either enhance it or not. All buildings except Portcullis House have deep plans, a fact that usually puts more limits in tempering internal conditions than in a narrow plan office building.

type\building	SSEES	Portculis House	Swiss RE	Heelis	NAW
Site location	urban	urban	urban	sub urban	sub urban
Climate profile	temperate	temperate	temperate	temperate	temperate
cooling strategy	natural ventilation + evaporative coooling	HVAC + ground cooling + active façade	natural ventilation + HVAC + active façade	natural ventilation + night cooling	natural ventilation + mixed-mode + ground cooling
plan type	deep plan	narrow plan	deep plan	deep plan	deep plan
Thermal mass	floor, ceiling, wall	ceiling, interior finishes	none	ceiling, floor	floor

Table 5-2. Building design characteristics for the case study buildings.

5.3 Implementation of sustainable cooling techniques

A mixture of various sustainable cooling techniques was observed in the case studies. Table 5-3 summarises the diversity of the techniques implemented in each case study.

For the reduction and modulation of the external heat gains all buildings were found to have high performance building envelopes. However, the designers of both Portcullis House and Swiss Re suggested a climate-active facade to enhance the performance of the envelope and to achieve desired internal temperatures. Nevertheless, it should be noted that this active ventilative approach puts more limits in natural ventilation by sealing the façade of a building.

Sustainable Cooling Techniques	SSEES	Portculis House	Swiss RE	Heelis	NAW
reduction and modulation of external heat gains					
high performance building envelope	•	•	•	•	•
climate-active façade		•	•		
reduction and modulation of internal heat gains					
atrium	•	•	•	•	
daylight strategy	•	•	•	•	•
Direct and Indirect Ventilative Cooling					
natural ventilation	•		•	•	•
night ventilation		•		•	
mixed-mode		•	•		•
Cooling Energy From Renewables					
ground (air)					
ground (water)		•			•
lake-sea (water)					
Sustainable Distribution Systems					
displacement ventilation		•			•
chilled beams and ceilings					
slab (water)					
slab (air)					
Low-Energy Cooling Technologies					
evaporative cooling	•				
desiccant cooling					
free cooling					
free cooling with heat recovery		•	•		

Table 5-3. Sustainable cooling techniques implemented on the case study buildings

Except for the external heat gains, internal heat gains are also considered. Four out of five case studies –except NAW- had atriums incorporated in their design. The incorporation of an atrium in the design always plays a diverse role; it is used for the optimisation of daylight penetration but also for ventilation purposes. In the case of Heelis, the existence of a deep plan suggested the need for two atriums spread within the plan, which act as the lungs of the building providing fresh air and natural light. At the same time, Swiss Re's designers recommended the triangular atriums in order to find a way in introducing fresh air from outside to inside the building because the rest of the facade is totally sealed. A similar approach was found for SSEES, where the sealed facade constrained the use of the light well, which plays the role of an atrium.

Moreover, daylight strategy is considered to be a crucial factor for sustainability playing also a significant role in the cooling strategy; it reduces energy consumption for lighting, while at the same time with the optimisation of natural light heat gains from artificial light are reduced. All five case studies had a good daylight strategy integrated in their design. Designers carefully considered the penetration of natural light in the buildings by the use of transparent elements like glass either in the facades or in the atriums. In the case of NAW, designers tried to take the most advantage of daylight by reflecting it to the inside with the use of external reflecting surfaces.

With regards to ventilative cooling, natural ventilation is much appreciated by most designers during summer, but is supplemented either by night ventilation in the case of Heelis or by evaporative cooling in the case of SSEES. It should be noted that mixed-mode approach seems more reliable and provides a better control of internal conditions as in the case of the other three buildings. Displacement ventilation is suggested for both Portcullis House and NAW additionally with ground cooling; the latter is much preferred because its cooling capacity is of the highest ones, rising up to $100W/m^2$. Chilled beams-ceilings and slab cooling is not observed in any of the case studies, even though its cooling capacities are also high.

It should be mentioned that the most important part in the sustainable cooling of buildings is the integration of technologies and services in the design of a building. As seen in the table the first two categories of sustainable cooling techniques, that is reduction and modulation of heat gains and ventilative cooling, are much appreciated by the designers for the majority of the buildings. They comprise the most energy and cost efficient methods and are mostly related with the building design. In this way, in all case studies the use of technologies is minimised by architects and engineers in order to decrease cooling loads of the buildings and thus diminish significantly their energy consumption.

5.4 Occupant satisfaction survey

type\building	SSEES	Portculis House	Swiss RE	Heelis	NAW
occupant satisfaction survey	-	-	-	done in 2006	-

Table 5-4. Occupant satisfaction survey for the case study buildings.

Heelis was the only building, where an occupant satisfaction survey was done after the suggestion of the architects. Considering occupant's satisfaction in order assess the buildings thermal performance the survey helped to define which parts of the design strategies were strong and weak and where there was a need of improvement. Feedback from the occupants helped the building manager and the design team to fine tune the building.

A thorough occupant survey with a satisfactory sample conducted in such a way that would give sufficient feedback was difficult for any of the buildings. Permission by the facilities department of each building was essential but was unlikely to be issued for security reasons in some cases (PH and SR). However, a first approach in this field was achieved with the cooperation of the facilities manager of NAW, where feedback was given by 20 occupants of the building. Some first impressions regarding the problems regarding ventilation and cooling were detected by the answers.

It should be emphasized that a good relationship and co-operation between the design team and the facilities department is essential to end up in a good building performance. Moreover, robust routine monitoring of internal temperature, energy consumption and CO_2 emissions from the BMS as well as setting up energy management procedures for the future are essential to assess the real thermal performance of a building.

5.5 Operational performance

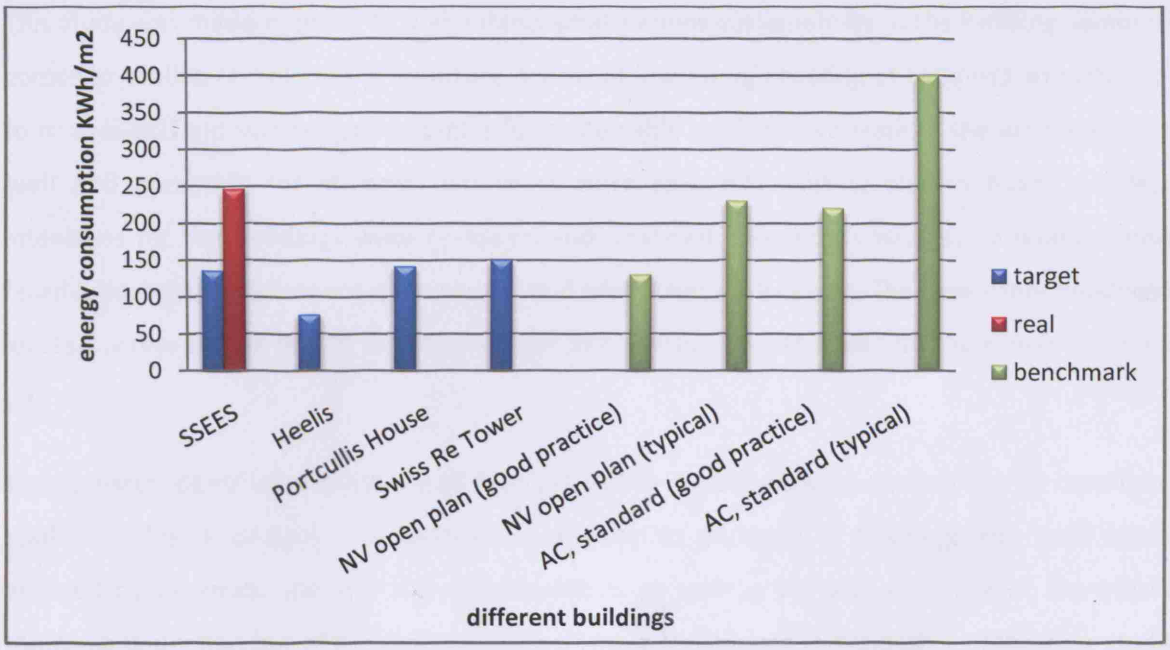


Figure 5-1. Comparison of target, real and benchmarks in energy consumption of buildings.

Referring to operational performance, on the one hand SSEES target energy consumption is 130KWh/m^2, which is similar to the good practice naturally ventilated open plan, on the other hand the real energy consumption is almost double, recording 250KWh/m^2. Thorough consideration by the designers should be done to detect in which ways the energy consumption is much more than the predicted.

High standards of energy consumption have been also set by the designers for Heelis, Swiss Re and Portcullis House; the figures are 75KWh/m^2, 150KWh/m^2 and 141KWh/m^2 respectively. As seen in figure 5-1 they are far below the air conditioned good practice and typical benchmarks. However, measurements for real energy consumption are not known; in this way the above mentioned figures are not comparable.

6. Conclusion

This study was made in order to understand what defines sustainability in the building sector when it comes to cooling techniques. A literature review of low-energy cooling of buildings was done in order to re-evaluate and summarise strategies for sustainable cooling. Five state of the art projects, already built and operating for at least two years were selected; existing studies based on designers' intentions for the buildings were reviewed and analysed. Key words such as ventilation, envelope, facade, daylight, performance were sought and addressed the analysis. The case study buildings are all located within the UK and in this manner the whole research was based on the climatic conditions of UK.

The research identified a summary of the sustainable cooling techniques that can be considered and applied to future designs. The techniques respond to all types of buildings and their selection is affected by micro-climate and site considerations as well as the size and type of the buildings. A thorough understanding of the incorporation of these techniques in the design of the case studies was achieved in order to figure out areas of strengths and weaknesses. However, results based on actual performance of the buildings were difficult to be reached due to lack of data and information in this field.

Results from the analysis create the following baselines:

• Sustainable cooling of buildings is a methodical process and needs to start from the early stages of the design of buildings. Architects together with engineers should co-operate and find clever ways of integrating building services and cooling technologies in the design of buildings.

• The most crucial part of the design that can provide low-energy cooling is the ventilation strategy together with the building envelope performance. A good interaction of fabric and ventilation within a building, as for example in the case of Portcullis House, can lead to significant energy savings and better performance during the summer period to avoid overheating.

• Daylight strategy is a critical key for the sustainability. Artificial lighting can cause excessive energy consumption; therefore, natural light penetration should be optimised by the designers, as it had been in most of the case studies.

Definition and selection of sustainable cooling techniques is important to avoid overheating during hot period. Detailed estimation of required cooling loads of a building can define the selection of the sustainable cooling techniques, according to their cooling capacities. However, the evaluation of the sustainable cooling techniques applied to a building is also significant. Further research in the field is necesarry.

Comparison of the real performance of a building with the design targets is important to evaluate the building's thermal behaviour, especially during summer. Benchmark and target values for a building's performance, regarding daylight factors, energy consumption and CO_2 emissions, are usually more optimistic than the actual data monitored, as in the case of SSEES. Moreover, post occupancy evaluation can give significant feedback regarding internal conditions' satisfaction throughout occupant satisfaction survey, as in the case of Heelis. In this way, there is room for improvement in the following areas:

• Thorough examination of daylight factors in every area of a building's floor plate and all floors to ensure desired distribution of natural light. An evaluation can be done comparing with the design targets of daylight factors.

• Robust monitoring of internal temperature and relative humidity from the BMS to help fine-tune the building. Fine-tuning of ventilation controls should also be considered in order to avoid overheating during summer period and also avoid contradicting mechanisms and occupants' misuse of manual controls.

• Evaluation of occupants' satisfaction of internal thermal comfort through the conduction of an occupant satisfaction survey. However, the sample should be sufficient enough to provide solid responses and reach with reliable results for the building thermal performance.

However, the cooling techniques of a building should not be considered separately, but together with the heating strategies during the winter period. Key issues that should be considered thoroughly during both hot and cold period include the following:

• Ventilation considerations are important because they comprise the most important heat losses in a building during the cold period.

• Building envelope insulation also comprises a significant issue, because of the great amount of heat losses through building fabric during winter.

• Sun shading is also important because it might cause opposite results during the cold period, like losing the desired effects of solar gains.

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8. Appendix

ITEM 1-10 Sensible Heat only	AREA, A m^2	FACTOR F (Circle the factors applicable)			LOAD F*A
1. Direct solar radiation: (Figure all windows for each exposure, but use only the exposure with the largest load)		For glass black reduce factor by 50%: for storm windows or double glass reduce factor by 15%.			
		No. Shading	Inside Shade	Outside Awn.	
North-east		190	79	63	
East		158	126	79	
South-east		237	95	63	
South		237	111	63	
South-west		347	142	95	
West		473	205	111	
North-west		379	158	95	
2. Window Transmission: (Total of all windows)		ΔT = (Outside T_{db} – Inside T_{db})			
Single glass		$32.26136 + 4.42684 * \Delta T$			
Double glass of glass block		$0.46241 + 3.025756 * \Delta T$			
3. Walls:					
No insulation (brick, frame etc.)		$8.3932 + 1.21465 * \Delta T$			
1 in insulation		$1.6405 * \Delta T - 1.2103$			
2 in or more insulation		$4.8094 + 0.43592 * \Delta T$			
4. Partitions:		$1.14461 * \Delta T - 0.179986$			
5. Roofs:					
(a) With vented air space and:					
No insulation		$48.82143 + 1.54762 * \Delta T$			
No insulation with attic fan		$12.68333 + 0.418599 * \Delta T$			
2 in insulation		$13.810 + 0.4350 * \Delta T$			
4 in insulation		$1.332 + 0.82311 * \Delta T$			
(b) Flat with no air space and:					
No insulation		$36.81435 + 1.37692 * \Delta T$			
1 in insulation		$73.67258 + 2.7099 * \Delta T$			
1.5 in insulation		$24.01056 + 0.708693 * \Delta T$			
3 in insulation		$16.80943 + 0.435918 * \Delta T$			
6. Ceiling: (under unconditioned room only)		$2.820 + 1.144611 * \Delta T$			
7. Floor: (Omit if over Basement crawl space or slab)					
Over unconditioned room		$0.984077 - 2.7099 * \Delta T$			
Over open crawl space		$0.470845 + 1.482207 * \Delta T$			
8. Outside air:		20 frequent door usage			
Per m^2 of floor area		$2.010575 + 0.708692 * \Delta T$			
9. People:					
10. Light & Fixtures					
11. Sub-total					
12. Latent heat allowance	30 % of item 11				
13. Total cooling load	Sum of 11 and 12				
14. Cooling load recommended					

Figure 1. Modified cooling load estimation form. (Source: Ansari at al., 2005 pp. 210)

UKCIP02 climate change scenario	IPCC SRES emissions storyline	UKCIP socio-economic scenario title	Description
Low Emissions	B1	Global Sustainability	Clean and efficient technologies; reduction in material use; global solutions to economic, social and environmental sustainability; improved equity; population peaks mid-century
Medium-Low Emissions	B2	Local Stewardship	Local solutions to sustainability; continuously increasing population
Medium-High Emissions	A2	National Enterprise	Self-reliance; preservation of local identities; continuously increasing population; economic growth on regional scales
High Emissions	A1F1	World Markets	Very rapid economic growth; population peaks mid-century; social, cultural and economic convergence among regions; market mechanisms dominate.

Figure 2. Characteristics for UK climate change scenarios (Source CIBSE TM 36, 2005 pp. 4)

Base temp. / °C	Monthly heating degree-days (/ K·day) for stated base temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	147	142	109	74	23	6	1	1	5	24	78	128
12	208	196	167	121	51	16	3	4	14	51	124	185
14	270	253	229	177	93	39	11	13	36	92	180	246
15.5	316	296	276	222	132	66	26	29	63	134	225	292
16	332	310	291	236	144	76	32	35	72	148	240	308
18	394	366	353	296	201	125	71	74	123	208	300	370
18.5	410	379	369	310	216	139	82	86	137	223	315	385
20	456	422	415	355	261	180	118	124	180	270	360	431
Base temp. / °C	Monthly cooling degree-hours (/ K·h) for stated base temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5	1214	1030	1640	2497	4952	6575	8529	8350	6488	4726	2473	1550
12	1	3	16	147	902	1868	3388	3228	1781	641	70	10
18	0	0	0	5	90	222	541	410	81	3	0	0

Figure 3. Monthly heating degree day and cooling degree hours for Cardiff. (Source: CIBSE TM 41 2006 pp. 2-13)

Base temp. / °C	Monthly heating degree-days (/ K·day) for stated base temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	150	140	99	61	16	2	0	0	4	22	84	132
12	207	192	151	101	37	8	1	2	11	46	130	187
14	267	247	208	150	72	24	6	8	28	86	184	246
15.5	314	290	255	192	105	45	16	18	51	124	228	293
16	329	304	269	206	117	52	20	23	59	135	243	307
18	391	360	331	264	168	91	45	50	100	192	302	369
18.5	406	373	345	277	182	102	55	58	113	207	317	384
20	453	417	393	323	224	138	82	87	152	253	362	431
Base temp. / °C	Monthly cooling degree-hours (/ K·h) for stated base temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5	1347	1216	2166	3236	5935	7820	9965	9630	7232	5101	2507	1622
12	8	20	109	443	1626	2972	4787	4467	2454	962	158	43
18	0	0	2	32	274	635	1388	1158	308	33	0	0

Figure 4. Monthly heating degree day and cooling degree hours for Heathrow. (Source: CIBSE TM 41 2006 pp. 2-14)

1 naturally ventilated cellular

- A simple building, often (but not always) relatively small and sometimes in converted residential accommodation.
- Typical size ranges from 100 m² to 3000 m².

The domestic approach, with individual windows, lower illuminance levels, local light switches and heating controls helps to match the operation with the needs of occupants and tends to reduce electricity consumption in particular. There also tend to be few common facilities. Catering often consists of the odd sink, refrigerator and kettle.

2 naturally ventilated open-plan

- Largely open-plan but with some cellular offices and special areas.
- Typical size ranges from 500 m² to 4000 m².

This type is often purpose built, sometimes in converted industrial space. Illuminance levels, lighting power densities and hours of use are often higher than in cellular offices. There is more office equipment, vending machines etc, and more routine use of this equipment. Lights and shared equipment tend to be switched in larger groups, and to stay on for longer because it is more difficult to match supply to demand.

3 air-conditioned, standard

- Largely purpose-built and often speculatively developed.
- Typical size ranges from 2000 m² to 8000 m².

This type is similar in occupancy and planning to building type 2, but usually with a deeper floor plan, and tinted or shaded windows which reduce daylight still further. These buildings can often be more intensively used. The benchmarks are based on variable air volume (VAV) air-conditioning with air-cooled water chillers; other systems often have similar overall consumption but a different composition of end use. (See Good Practice Guide (GPG) 290 ' Ventilation and cooling option appraisal – a client' s guide' .)

4 air-conditioned, prestige

- A national or regional head office, or technical or administrative centre.
- Typical size ranges from 4000 m² to 20 000 m².

This type is purpose-built or refurbished to high standards. Plant running hours are often longer to suit the diverse occupancy. These buildings include catering kitchens (serving hot lunches for about half the staff); air-conditioned rooms for mainframe computers and communications equipment; and sometimes extensive storage, parking and leisure facilities. These facilities may be found in offices of other types, and, if so, can be allowed for by adding together energy consumption by appropriate end uses from different office types in Appendix B.

Figure 5. Four generic types of offices described in detail. (DETR, 2000 pp. 7)

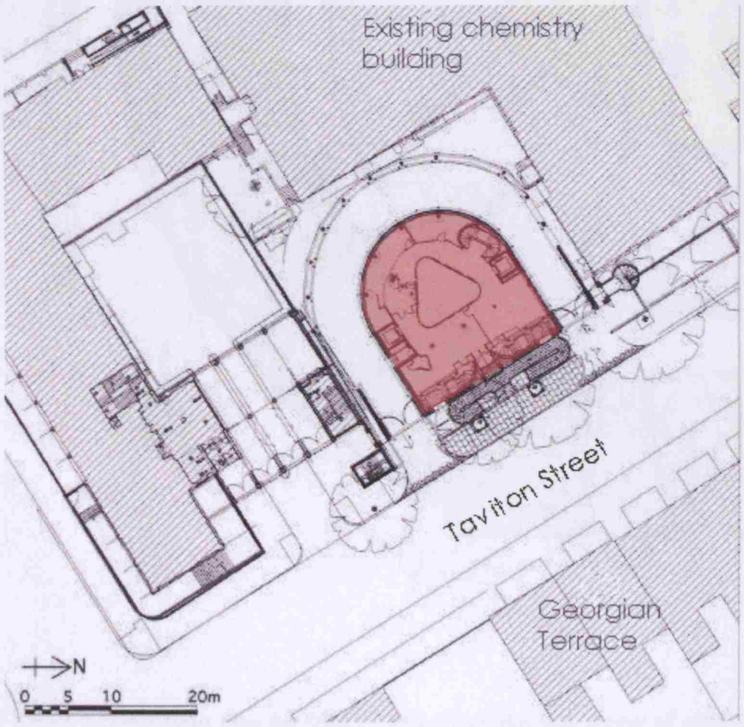

Figure 6. Site plan for School of SSEES. The building is highlighted in red. (Source: Short, 2004 pp. 195)

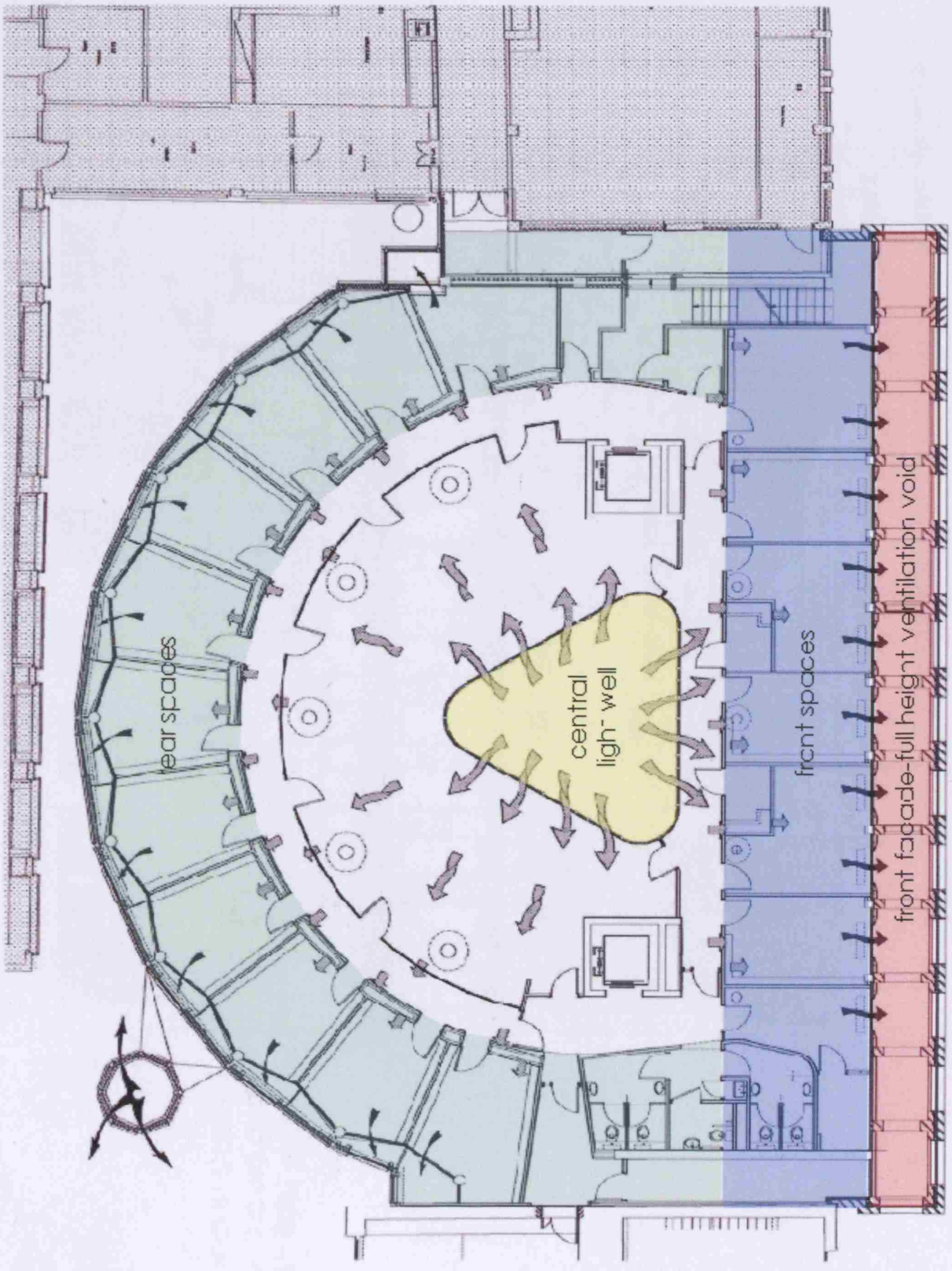

Figure 7. Third floor plan for SSEES highlighting the separation of different spaces for ventilation purposes. (Source: Short, 2004 pp. 196)

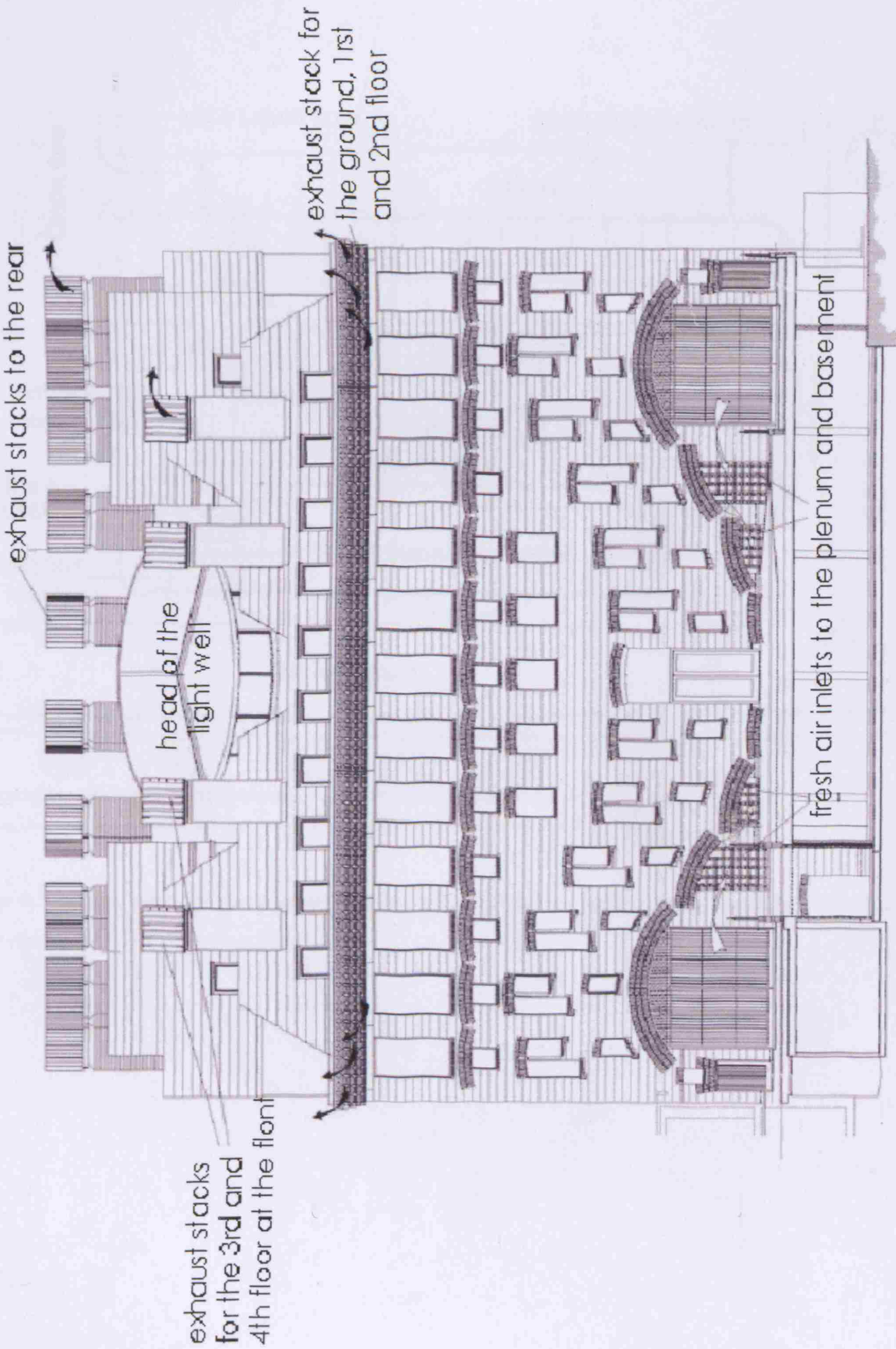

Figure 8. Principle elevation for the SSEES showing the air intake and exhaust.

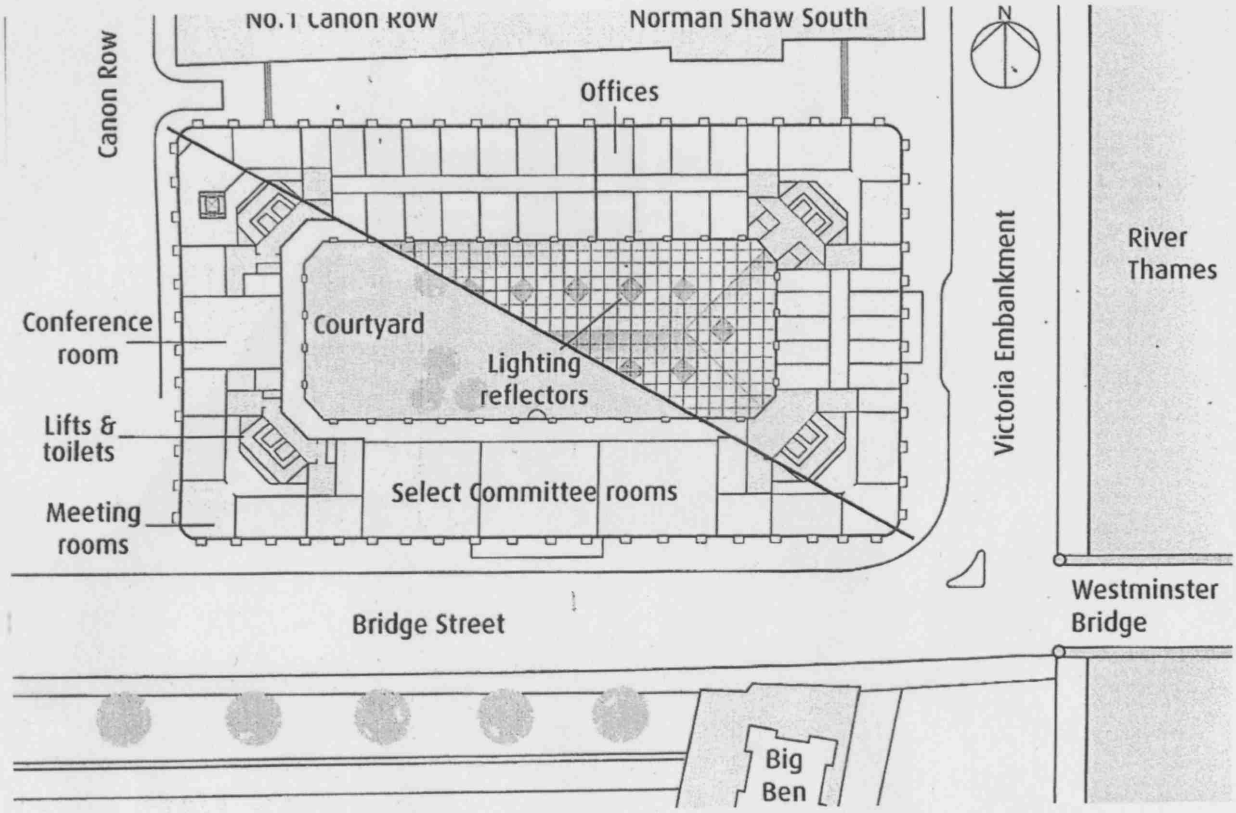

Figure 9. Site plan and floor plan showing half the ground floor and half the upper floors for Portcullis House (Source: Bunn, 2000 pp.25)

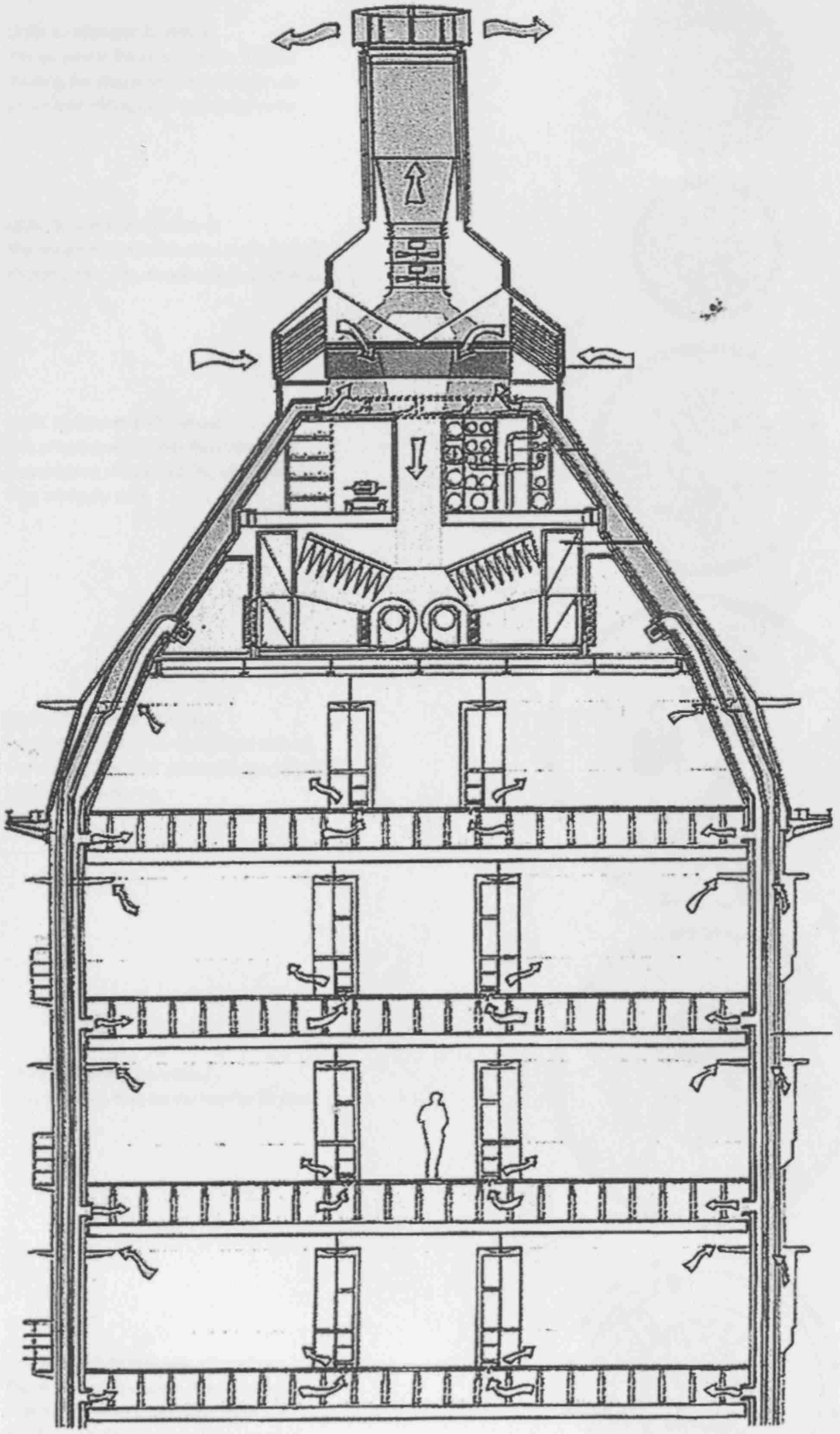

Figure 10. Cross section showing building services and ventilation strategy for Portcullis House

LEVEL 40 (diameter 22 metres):
The bar area at the summit of the building showing the circular staircase giving access to this level with a platform lift at its centre.

LEVEL 39 (diameter 27 metres):
The restaurant level also has to accommodate kitchens, WCs, lifts, escape stairs and services.

LEVEL 33 (diameter 43 metres):
This reflected ceiling plan shows the radial layout typical of floors 28–34, which do not have triangular atria.

LEVEL 21 (diameter 56 metres):
A typical office floor on the mid-rise lift bank. Note the six triangular atria creating orthogonal 'fingers' of floorspace.

LEVEL 6 (diameter 54 metres):
A typical office floor on the low-rise lift bank.

ENTRANCE LEVEL (diameter 49 metres):
The west-facing entrance lobby gives access to three sets of lift banks: low-, medium- and high-rise. Space to the east is allocated for retail use.

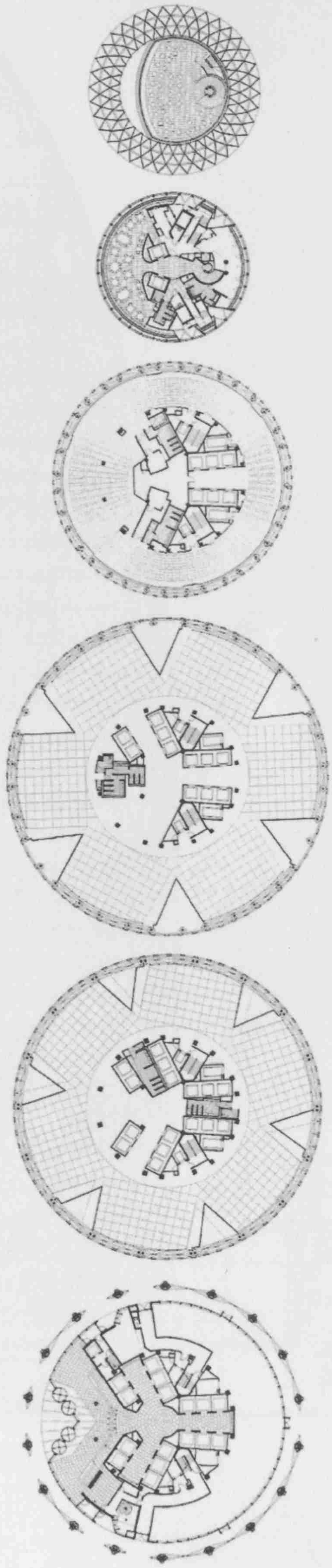

Figure 11. Floor plans in different levels of Swiss Re Tower. (Source: Powell 2006 pp. 75)

Figure 12. Section through Swiss Re Tower. (Source: Powell 2006 pp. 74)

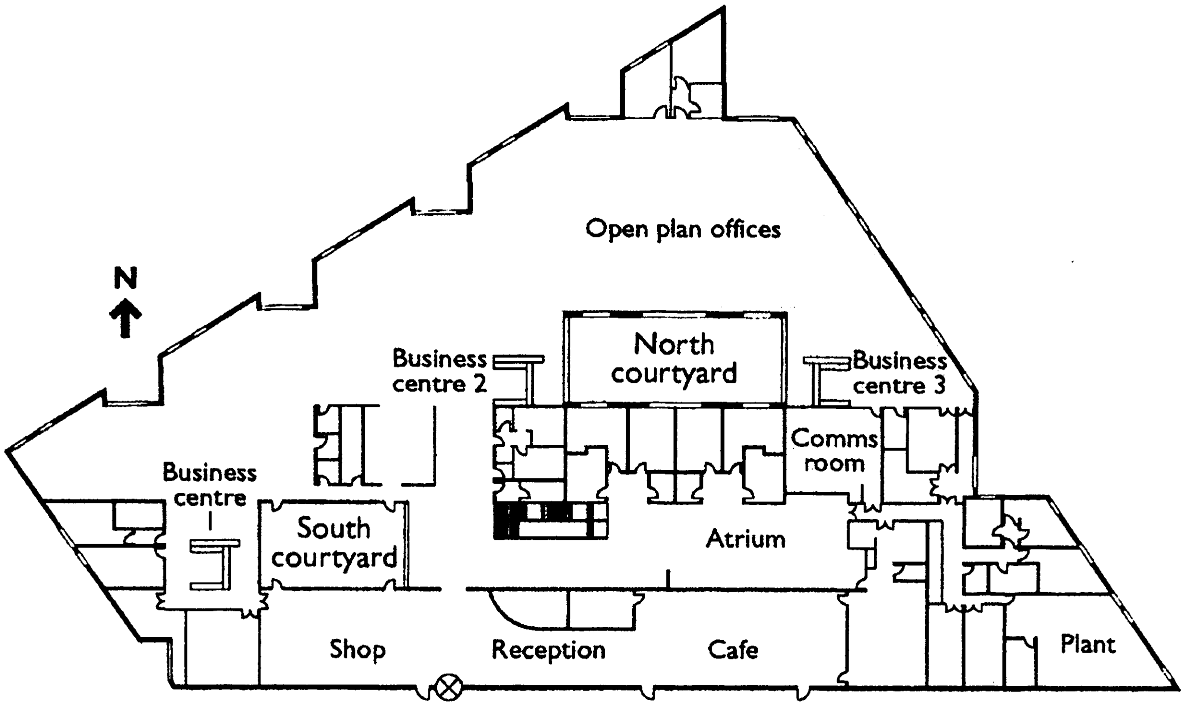

Figure 13. Ground floor site plan for Heelis building (Source: Morris, 2007, pp.11).

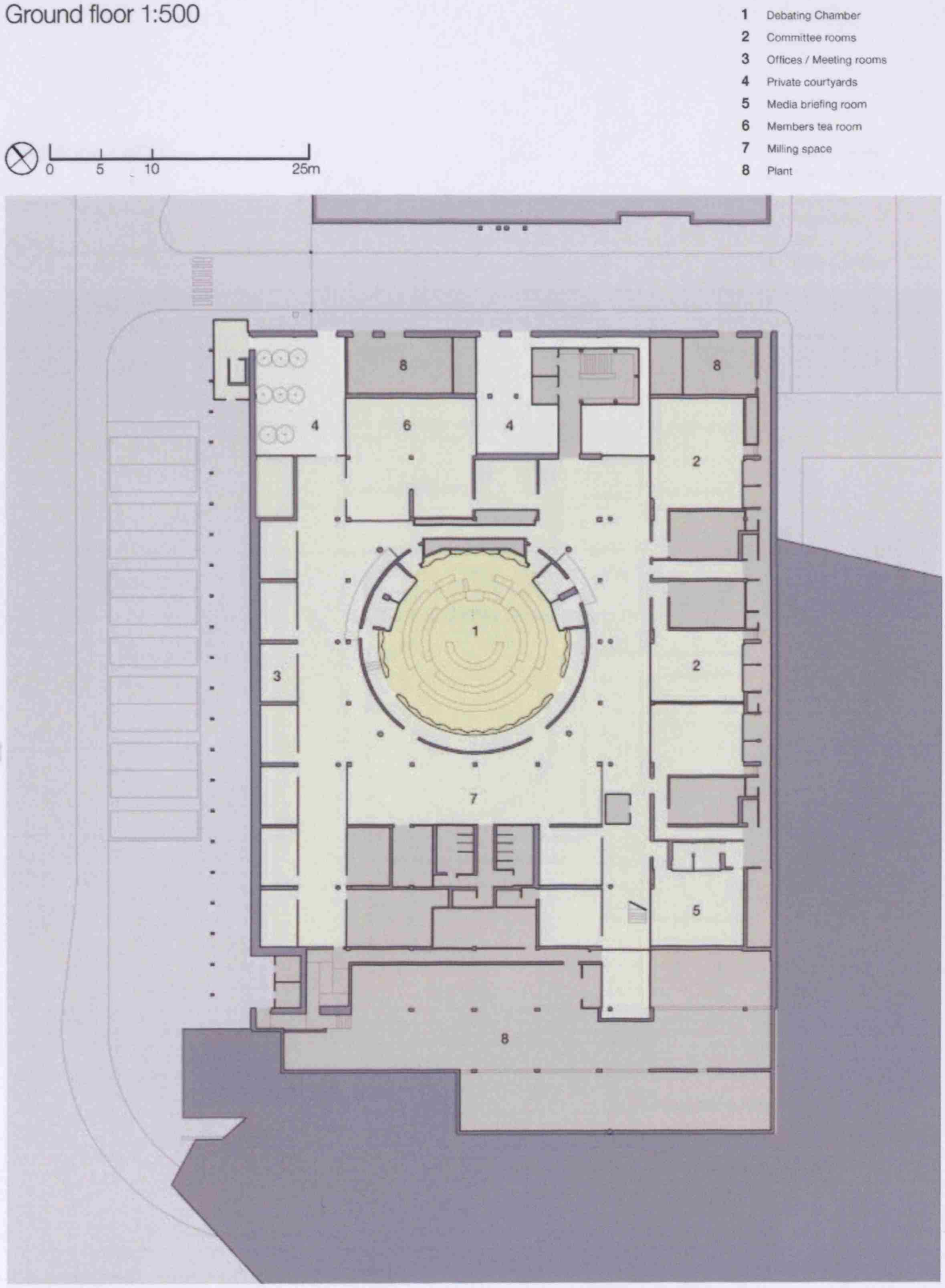

Figure 14. Ground floor plan - National Assembly for Wales

(Source http://www.richardrogers.co.uk/Asp/uploadedFiles/Image/News/RRP_4000_Drawings_P_060322.pdf)

Figure 15. First floor plan - National Assembly for Wales.

(Source http://www.richardrogers.co.uk/Asp/uploadedFiles/Image/News/RRP_4000_Drawings_P_060322.pdf)

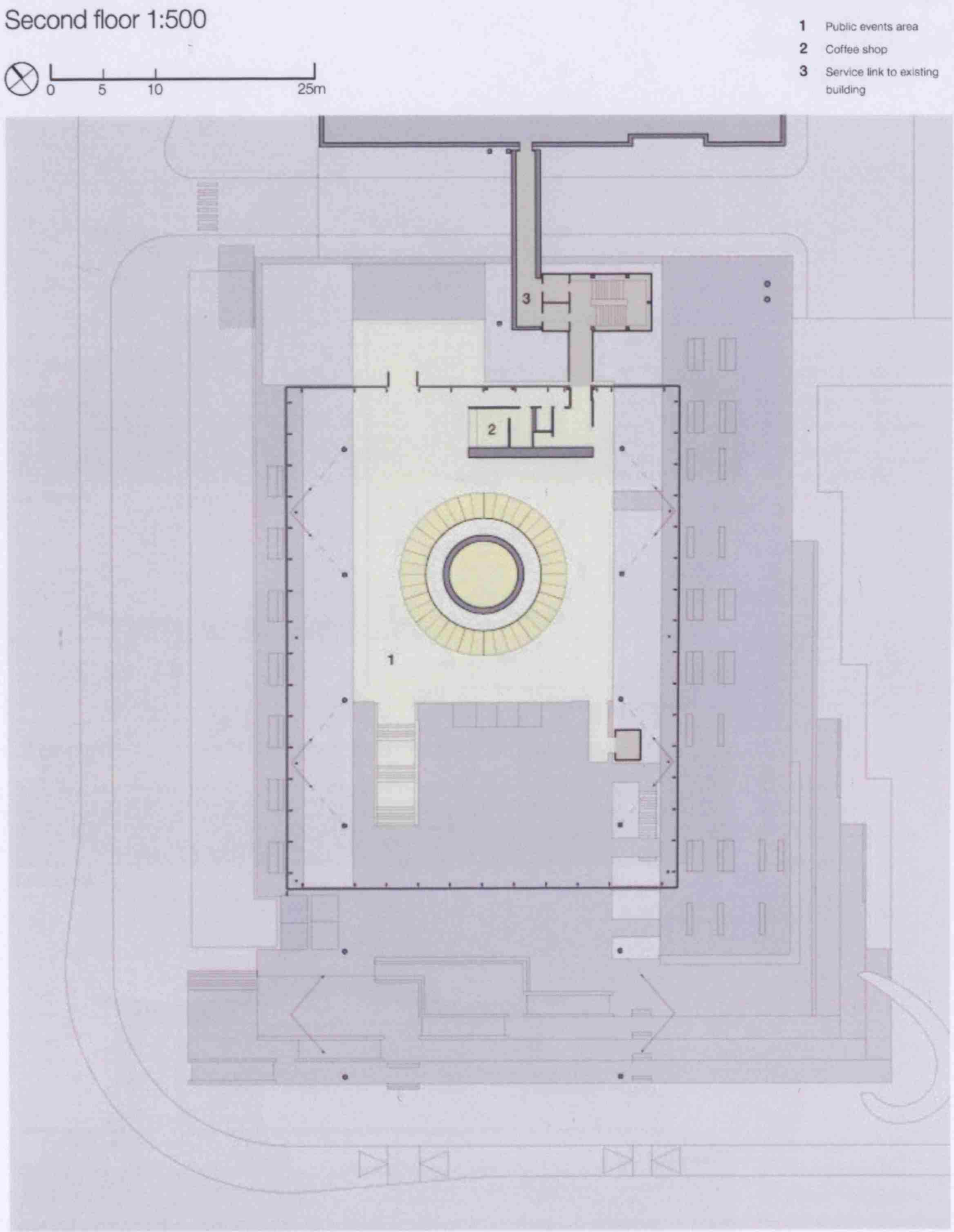

Figure 16. Second floor plan - National Assembly for Wales.

(Source http://www.richardrogers.co.uk/Asp/uploadedFiles/Image/News/RRP_4000_Drawings_P_060322.pdf)

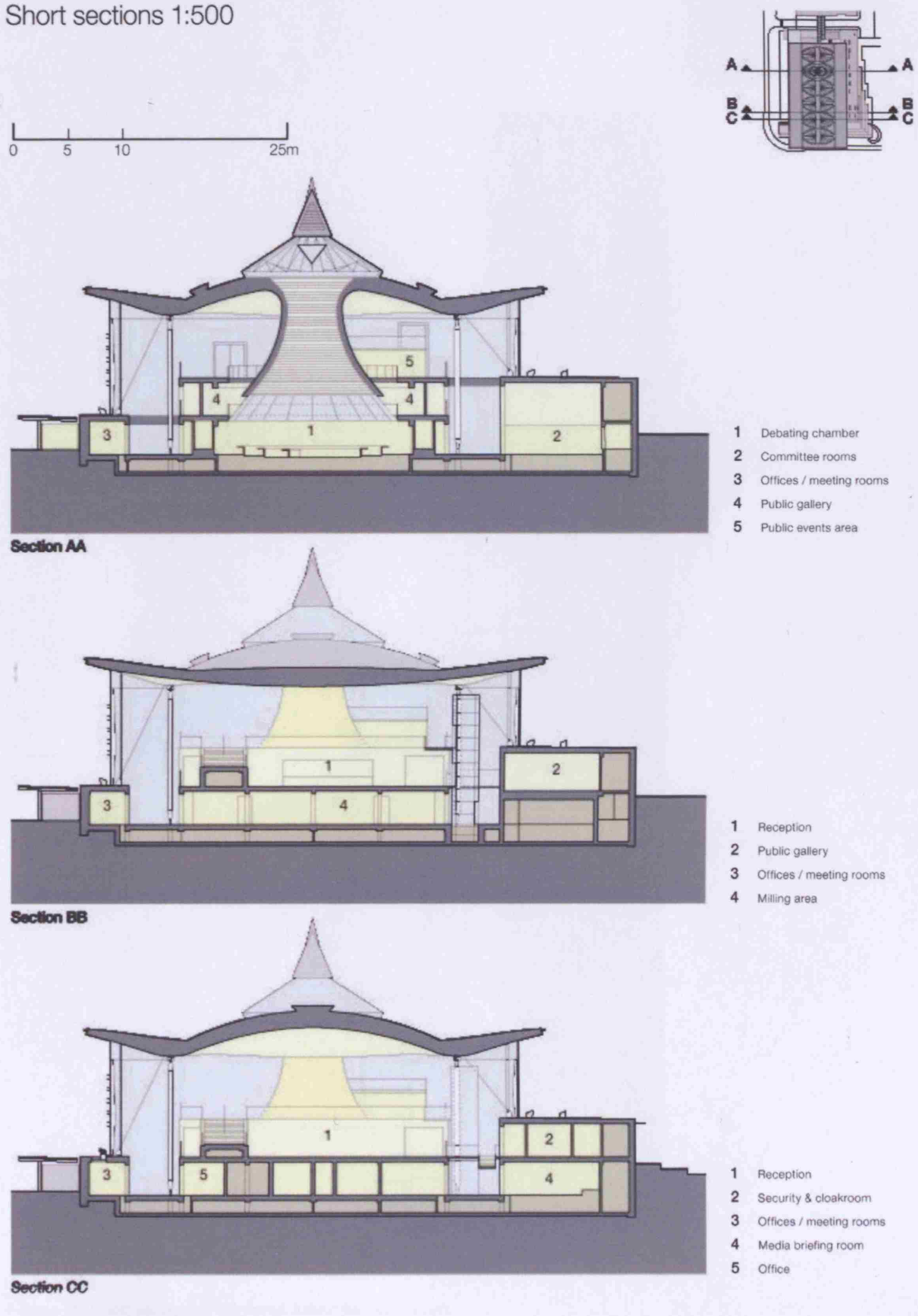

Figure 17. Short sections of National Assembly for Wales.

(Source http://www.richardrogers.co.uk/Asp/uploadedFiles/Image/News/RRP_4000_Drawings_P_060322.pdf)

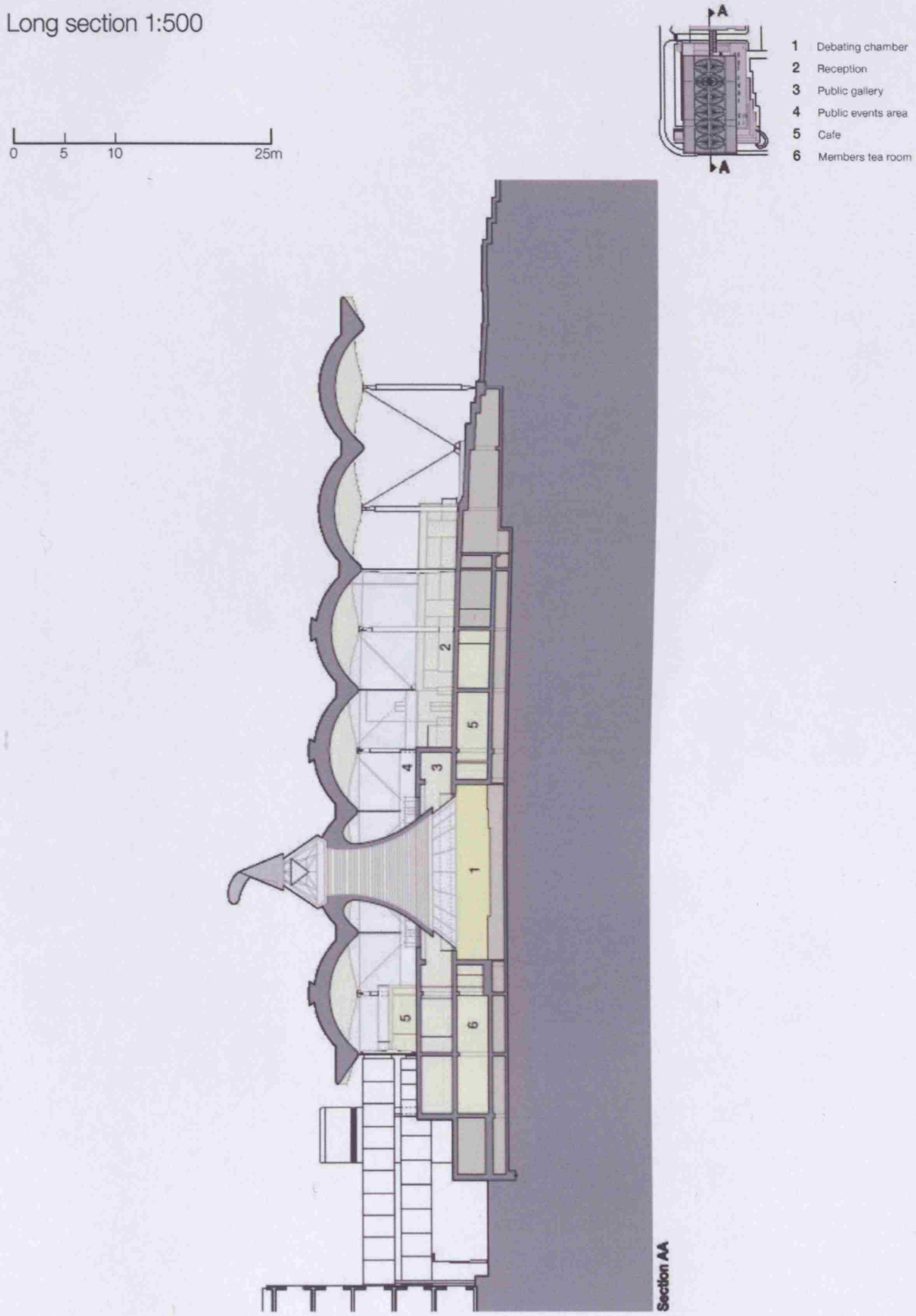

Figure 18. Long section of National Assembly for Wales.

(Source http://www.richardrogers.co.uk/Asp/uploadedFiles/Image/News/RRP_4000_Drawings_P_060322.pdf)